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The Differentiation of a Secondary Magma trough Gravitative Adjustment

By REGINALD A. DALY
Ottawa, Canada

With 2 textfigures

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The Differentiation of a Secondary Magma through Gravitative Adjustment.

By Reginald A. Daly, Ottawa, Canada.*)

(With 2 textfigures.)

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Introduction:
the dependence of petrology upon structural geology.

Sooner or later experience must teach every careful field student of gneous rocks the truth of the principle of magmatic differentiation. That principle is, indeed, so generally accepted by petrologists that it may be considered as a permanent acquisition in the theory of their science. Yet it is a long step from the recognition of the doctrine to its application to the origin of igneous rocks as actually found in the earth's crust. The principle becomes really fruitful, in fact becomes first completely understood and realized, when certain chief problems have been solved.

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Among those problems there are naturally three that are fundamental. Only after they are solved has petrology done that which it has set out to do, namely, determine, under the difficult conditions of earth study, the true nature and genesis of rocks. The first insistent question is, in every case, what was the magmatic mixture or matrix from which the material of the existing rock-mass or rock-masses was produced through differentiation? The second question is, how far did the differentiating process operate? The third insistent question is, what was the process of differentiation itself?

All three problems are interdependent and involve a study in structural geology. They cannot be solved simply by acquiring even the fullest information to be derived from single plutonic contacts, nor, as a rule, from such as may be derived from entire ground-plan contact lines. On the other hand, it is necessary that, more or less completely, the petrologist shall know his magma chamber as the chemist or metallurgist knows his crucible. No student of fused slags can obtain safe results from the profoundest examination of merely one surface or one section of the fused product. He must think in three dimensions. In the same way, the petrologist attempting to unravel the complex history of a magma chamber, should, ideally, know its general shape, size and contents as well as the method by which the chamber has been opened within the earth's crust. Until these conditions are fulfilled his problem of rock-genesis through magmatic differentiation must remain wholly or in part indeterminate.

The geologist knows how hard those conditions are. He is dependent upon erosion's rendering his contacts accessible; yet erosion destroys surfaces of contact. He can find no bottom to the chamber of stock or of batholith, though large-scale differentiation is most commonly evinced in stocks and batholiths. It is not to be wondered at that, notwithstanding the great number of described instances of magmatic differentiation, the phenomenon itself is so little understood or that the origin of the igneous rocks is still shrouded in the mists of hypothesis. In view of the difficulties surrounding the study, the discovery of single cases where the requisite field conditions are tolerably well fulfilled, merits special statement. Descriptions of bodies differentiated in chambers of known form are in the highest degree rare. Nevertheless, it is precisely in the light of these rare cases that the laws of differentation can be most intelligently discussed.

Such an instance is described in this paper. It refers to an exceptionally clear example of differentiation within a magmatic chamber, the crystallized contents of which can now be examined from top to bottom of the chamber. The form and geological relations of the chamber are sufficiently well determined to serve for the discussion of the magmatic problem. The general nature of the magma whence differentiation has evolved the existing igneous rocks is believed to be deducible from the field and chemical relations. That compound magma was itself derived, owing its composition to the digestion or solution of acid sedimentary rocks in an original gabbro magma. Finally, the facts seem indisputable as to the nature of the method by which the differentiation took place. The splitting of the magma may have roughly followed eutectic laws, but the actual segregation of the sub-magmas appears to have been directed by gravity, producing simple stratification in the chamber. The less dense sub-magma of splitting overlies the denser sub-magma of splitting.

A note on the Moyie Sill, the example to be discussed in the following pages, was published in the American Journal of Science, September, 1905, p. 185. In that paper stress was laid upon the repeated occurrence of similar phenomena in other regions. The comparison need not here be repeated, although its value is evidently of primary importance to the main conclusions regarding the mode of rock-genesis common to all the occurences. The present paper will be occupied more strictly with the Moyie Sill rocks of which Professor M. Dittrich and Mr. M. J. Connor have made chemical analyses additional to those published in the earlier paper. The new information derived from these analyses as well as from supplementary microscopic study goes far towards corroborating the views originally held by the writer.

General Geology of the Purcell Mountain Range.

During the field season of 1904 the writer developed a geological structure section along the 49th Parallel of latitude between Port Hill, Idaho, and Gateway, Montana, the two points where the Kootenay River crosses the boundary line between Canada and the United States. It was found that the mountains traversed by the section — the Purcell Range — are for the most part composed of two very thick siliceous sedimentary formations. The two are conformable and, while locally unfossiliferous, seem to be the stratigraphic equivalents of Cambrian and pre-Cambrian sedimentaries in the Rocky Mountains proper.

The lower formation has been called the Creston quartzite. It is a remarkably homogeneous, highly indurated, light-gray to medium-gray sandstone, generally thick-platy in structure but occasionally interrupted by thin intercalations of argillaceous material. The dominant rock is composed of quartz, feldspars and micas. The total thickness of the formation is at least 2670 meters in the vicinity of Port Hill; its base was not directly observed.

Immediately overlying the Creston quartzite is the conformable Kitchener quartzite which shows a minimum thickness of 1950 meters. This formation is distinguished from the Creston quartzite chiefly by the rusty colour of the outcrops, by thinner bedding, and by a greater proportion of micaceous cement once somewhat argillaceous. The old sandstone is also notably feldspathic and, like the Creston quartzite, often approaches a true arkose in composition.

Dark-coloured red, brown and gray shales with thin intercalations of gray quartzite conformably overlie the Kitchener quartzite. The series, totalling 1050 meters in thickness, has been grouped under the name of the Moyie argillite. The formation appears but twice in the section and then only in comparatively small areas.

This great group of formations has been strongly dislocated in the building of the mountains. A few open folds broken by faults appear in the eastern half of the belt, but the deformation has been due in general to the tilting of monoclinal blocks separated by normal faults and, more rarely, by thrusts. The tilting of the beds ranges through all angles up to verticality, but the average dip is less than forty-five degrees. In consequence of the deformation and subsequent denudation the edges of more than 5600 meters of well-bedded ancient sediments are now exposed. There have also come to light a number of thick sills of gabbro intruded at various horizons into the Kitchener quartzite and the upper part of the Creston quartzite.

The intrusion and crystallization of the gabbro are believed to have taken place before the upturning of the sedimentaries. One leading evidence for this is found in the existence of a conspicuous sheet of extrusive basic lava occurring at the upper limit of the Kitchener quartzite. The lava is clearly contemporaneous with that quartzite and flowed out over the ripple-marked surface of the sandstone while the latter lay flat on the sea-floor. There is field evidence that this lava flood was fed from one of the basic sills above mentioned. It is believed, therefore, that the intrusion of the sills occurred while the sedimentaries were still essentially in their original position.

The faulting and tilting have repeated the outcrops of certain of the sills. One of the thickest of them has been warped into one of the rare synclinal folds. The thickness of the sills varies from 30 meters to 840 meters.

Petrography of the sills in the Purcell Mountain Range.

The main body of each sill whether thick or thin was found to consist of a nearly constant type of hornblende gabbro. Macroscopically, it is a dark greenish-gray, medium grained rock of gabbroid habit. The principal variations in macroscopic character are due simply to the local coarsening of grain as so commonly seen in gabbros, or, secondly, to the local development of a more hornblendic phase in which feldspar is seen to be comparatively inconspicuous.

Microscopic examination confirmed the field impression of the relative uniformity of the material originally injected into the quartzites. The essential minerals proved to be hornblende and triclinic feldspar; the accessory constituents always include titanite, titaniferous magnetite and apatite with a more or less notable amount of interstitial quartz. Often biotite and, more rarely, orthoclase occur as additional accessories. Epidote, zoisite and chlorite are the chief secondary minerals.

None of these minerals presents unusual characteristics and their description warrants but few words. The hornblende is primary; its colour green, absorption strong ($\mathfrak{b} = \mathfrak{c} > \mathfrak{a}$). The extinction on the cleavage plate runs from 13° to 14°. These properties and the total analysis of the rock show that it is a type of aluminous hornblende. It is idiomorphic against feldspar. The dominant plagioclase crystals belong to the species Ab_5An_6, but some crystals are zoned with anorthite in the cores. The average feldspar is basic labradorite near Ab_1An_2. The anhedra and minute crystals of magnetite, like the minute apatite needles, are often strikingly rare; titanite with the habit usual in gabbros is abundant. No pyroxenic mineral has been discovered in any phase of the rock; even in that which is quite fresh.

The following analysis, "Phase B", illustrates the chemical composition of the comparatively fresh gabbro from a sill outcropping about 13 kilometers east of the Moyie River. It may be taken to represent closely the normal rock of the sills.

Phase B.

SiO_2	51.92 %
TiO_2	.83
Al_2O_3	14.13
Fe_2O_3	2.97
FeO	6.92
MnO	.14
MgO	8.22
CaO	11.53
Na_2O	1.38
K_2O	.47
H_2O below 110° C	.10
H_2O over 110° C	1.07
P_2O_5	.04
CO_2	.06
	99.78
Sp. Gr.	3.000

Analyst: Professor Dittrich.

A fairly accurate optical determination of the weight percentages among the principal mineral constituents gave the result:

Hornblende	58.7 %
Labradorite	34.8
Quartz	4.0
Titanite and magnetite	1.4
Biotite	.9
Apatite	.2
	100.0

The two tables indicate that the rock is not a common type of gabbro. Calculation shows that the hornblende is of an unusually acid type and is low in alumina, with lime, magnesia and total iron oxides present in about equal amounts. The composition of the specially abundant amphibole and the presence of the accessory quartz chiefly explain the high acidity of the rock as a whole and also the comparative poverty in alumina. The rock is,

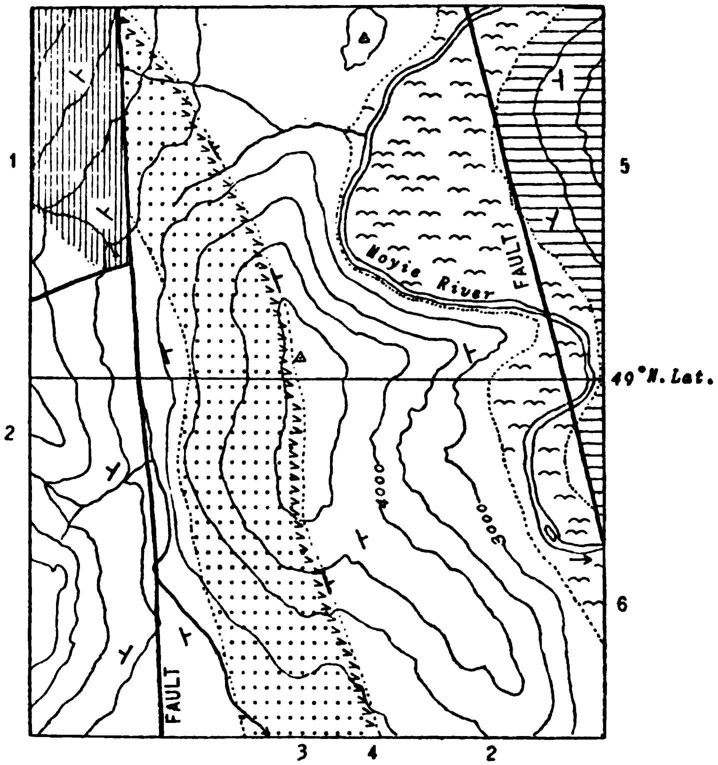

Figure 1.

Map of the Moyie Sill, taken from the plane-table sheet of the International Boundary Commission.

Explanation: 1 Moyie Argillite. 2 Kitchener Quartzite. 3 Hornblende gabbro. 4 Granite (acidified zone of sill). 5 Creston Quartzite. 6 Alluvium.

Conventional sign for strike and dip.

Isohypses in feet.

Scale 1 : 64000.

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thus, to be classed among the hornblende gabbros and yet must be regarded as an abnormal variety in that class. As already indicated, this abnormality persists in the average rock of all these great intrusive bodies.

The Moyie Sill — its petrography.

Within each one of the thicker sills, however, there is a systematic variation in composition. It is most striking in the case of the greatest of all the intrusions, that of the Moyie Sill. Its situation and relations are shown in Fig. 1 and 2.

Though the thickness of this sill is so great — 840 meters — the body is best described as a true sill or intrusive sheet. It preserves a nearly constant thickness for the 9500 meters through which the respective contacts have been followed in the field. A sill of similarly great thickness outcrops on a large scale about 14 kilometers to the westward and it is very possible that it is the Moyie Sill merely repeated by the strong block-faulting characteristic of the region. In any case the Moyie intrusive body has not the local development, the ground plan or sections of a typical laccolith. If its whole extent were known, it might prove to be of a form transitional between sill and laccolith. It will be seen, however, that, for the purposes of the following argument, a decision as to this matter of classification is not necessary. Of much greater importance is the fact that from end to end of the part of the sill mapped in Fig. 1, the exposure of the intrusive body is exceptionally perfect. Two complete sections were made across it and the writer feels reasonably certain from less full observations made at yet other points that the phenomena to be noted are not only duplicated on the two complete sections but characterize the whole exposure of the sill.

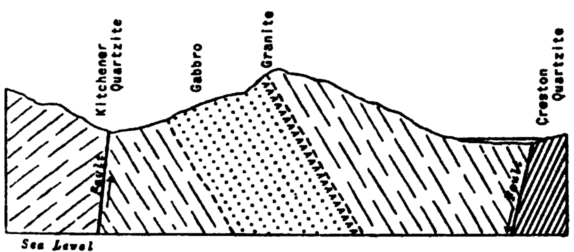

Figure 2.

Section of the Moyie Sill along line of the International Boundary.
Horizontal and vertical scales: 1 : 65000.

The one section was made exactly on the line of the international boundary (Fig. 2), the other along a wagon-road following the meridional valley west of the isolated mountain shown in Fig. 1. It was found in each case that, at the upper sill-contact, the igneous rock showed a remarkable variation from the usual type just described. For an average distance of about 45 meters measured perpendicularly from that contact, the sill-rock was, even in the field, at once referred to a species far removed from the gabbros. It evidently represented an acid, granitic zone in the sill.

The acid rock is gray, much lighter in tint than the gabbro, and without the deep green cast of the latter. The grain varies from quite fine to medium. Very often roundish fragments of bluish, opalescent quartz interrupt the continuity of the rock. These are considered to be of exotic origin as they were seen to graduate in size into larger block-fragments of quartzite (xenoliths) shattered of from the sill-contacts.

In order to determine the average composition of the acid zone and to show the approximate limits of lithological variation within it, fresh specimens were taken at three points in the section following the wagon-road. They were collected at respectively 4.5, 12 and 15 meters from the upper contact with the quartzite.

The specimen taken at 4.5 meters from the contact, and representing what may be called Phase E, has the macroscopic appearance of a finely granular gray granite. In thin section it is seen to be a micropegmatite with a hypidiomorphic granular structure sporadically developed in many parts of the section. The crystallization is confused and does not show the regular sequence of true granites. The essential constituents are quartz, micropegmatite, microperthite, orthoclase, oligoclase-andesine and biotite; the accessories include titaniferous magnetite, a little titanite and minute acicular crystals of apatite and rarer zircons. The characters of all these minerals are those normally belonging to common granites. The chemical analysis of the rock shows the mica to be magnesian.

A striking feature of this, as of the other phases of the acid rock, is the advanced alteration of the feldspars which are usually filled with dust-like aggregates of epidote, kaolin and muscovite. This alteration is believed to be due to magmatic after-action, probably the result of the expulsion of vapours during the solidification of the underlying gabbro.

The calculation of the quantitative mineralogical composition of the rock has been attempted by the Rosiwal method. In the process the secondary products were neglected and the feldspars were arbitrarily regarded as fresh.

The inaccuracy of the result is manifest but it does not affect the value of the comparison among all the phases of the sill. Especially between the gabbro and the acid zone the contrasts of quality emerge with the same clearness and certainty as characterize the related contrasts established in the chemical analyses.

The total chemical analysis of this Phase E is here given:

SiO_2	71.69 %
TiO_2	.59
Al_2O_3	13.29
Fe_2O_3	.83
FeO	4.23
MnO	.09
MgO	1.28
CaO	1.66
Na_2O	2.48
K_2O	2.37
H_2O-below 110° C	.14
H_2O over 110° C	1.31
P_2O_5	.07
CO_2	.13
	100.16
Sp. Gr.	2.773

Analyst: Professor Dittrich.

The most evident peculiarity is the low total for the alkalies; it accords with the relatively small proportion of feldspar present. Notwithstanding the abundance of free quartz the silica percentage is kept low by the comparative richness in biotite and by the magmatic alteration of the rock. The estimate of the mineralogical composition gave the following result in weight percentages:

Quartz	41.6 %
Sodiferous orthoclase .	32.5
Biotite	15.2
Muscovite	4.6
Microperthite	3.9
Oligoclase	1.0
Magnetite	1.0
Apatite	.2
	100.0

The second analyzed specimen of the acid zone, Phase D, is that collected at the point 12 meters from the upper sill-contact. It is closely allied in composition to the phase just described and is chiefly distinguished from the latter by a coarser grain and a different structure. Microscopic examination shows this rock to be eugranitic (hypidiomorphic granular) with small isolated areas of the micrographic intergrowth of quartz and feldspar. The constituents are nearly the same as in Phase E. Here, however, muscovite is an accessory so rare as not to enter the table of quantitative mineral proportions. True soda-orthoclase replaces nearly all the microperthite of the micropegmatitic facies. Calcite enters the list of secondary minerals.

The chemical analysis of Phase D is as follows:

SiO_2	72.42 %
TiO_2	.68
Al_2O_3	10.47
Fe_2O_3	.83
FeO	5.50
MnO	.16
MgO	.41
CaO	2.53
Na_2O	1.93
K_2O	2.94
H_2O below 110° C	.06
	97.93

	97.93 %
H_2O over 110° C	1.11
P_2O_5	.11
CO_2	.61
	99.76
Sp. Gr.	2.784

Analyst: Professor Dittrich.

The corresponding mineral composition in weight percentages was roughly determined thus:

Quartz	46.0 %
Soda-orthoclase	29.1
Biotite	22.0
Oligoclase	1.5
Magnetite	.5
Apatite	.5
Calcite	.4
	100.0

The high proportion of quartz, the very low percentages of the alkalies, yet lower than in Phase E, and the low percentage of alumina indicate that we have here again, as in Phase E, a quite abnormal kind of granite.

The Phase D′, collected at the point 15 meters from the upper sill-contact is unusually quartzose. It has nearly the same qualitative composition as Phase D but the structure is more like that of Phase E, being essentially that of a rather coarse-grained micropegmatite. The optical method gave the following weight percentages for the different constituents:

Quartz	57.1 %
Sodiferous orthoclase	24.9
Biotite	8.9
Muscovite	3.2
Calcite	2.5
Magnetite	1.9
Oligoclase	1.5
	100.0

It is clear that there is notable variation in the composition of the whole acid zone as represented in Phases E, D and D′. The apparently regular increase in acidity in the zone from above downwards is fortuitous. The zone is in reality irregularly streaked in many such phases carrying variable proportions of the mineral and oxide constituents. Whatever the cause, the magma of the acid zone was not homogeneous at the time of its solidification. To that fact is doubtless to be related the confused, rapid crystallization of the essential mineral constituents.

On the other hand, the rock of the acid zone in all its phases belongs to the granite family and stands at all points in contrast with the gabbro, the main constituent of the sill. Field and optical study show that the great body of this gabbro has the chemical composition already described as belonging to the sill gabbro occurring generally throughout the region i. e., Phase B. So evident was this fact that it was considered unnecessary to have the normal Moyie Sill gabbro specially analyzed. To appreciate the fundamental dissimilarity of the acid rock and the gabbro it is only necessary to glance at the tables of chemical and mineralogical analyses (Tables I. and II.).

Between the acid zone and the normal gabbro is an intermediate, transitional zone represented by Phase C, collected at a point 60 meters from the upper sill-contact.

Macroscopically, Phase C is quite closely similar to the normal gabbro. It is a dark greenish gray, granular rock of basic habit. Its essential minerals are hornblende, biotite and andesine; the accessories, quartz, orthoclase, titanite, titaniferous magnetite and apatite. The secondary minerals are zoisite, kaolin and epidote. The structure of the rock is in general the hypidiomorphic granular but local areas of micropegmatite are common in the section.

The total analysis of this phase gave the following result:

SiO_2	52.63 %
TiO_2	.62
Al_2O_3	16.76
Fe_2O_3	2.86
FeO	10.74
MnO	.38
MgO	4.33
CaO	6.17
Na_2O	1.41
K_2O	2.29
H_2O below 110° C	.12
H_2O over 110° C	1.17
P_2O_5	.33
CO_2	.10
	99.91
Sp. Gr.	3.020

Analyst: Professor Dittrich.

The quantitative mineral composition by weight percentages was determined (orthoclase not separately estimated but included in the andesine) thus:

Hornblende	49.4 %
Biotite	22.0
Andesine	16.5
Quartz	11.7
Apatite	.3
Magnetite	.1
	100.0

The abundant biotite and quartz go far to explain the differences between the chemical analysis here and that of the normal gabbro. It also appears from the analysis that the hornblende is here unusually aluminous. Chemically considered this intermediate rock has its nearest relatives among the diorites; yet the low feldspar content forbids our placing this rock variety in that family. Like both the gabbro and the granite it is an anomalous type.

Such are the conditions at the upper zone of contact within the great sill. Vastly different are those at the lower contact. In the field it is almost impossible to say that there is even the slightest systematic change, other than in a certain diminution of grain, as one passes downward in the sill. Crossing the thoroughly gabbroid rock for more than 700 meters of sill-thickness, the observer comes abruptly upon the quartzite without meeting any evident zone of acid igneous rock.

Yet microscopic and chemical study of the lower internal zone of contact shows that here, too, the rock is not quite the normal gabbro. Phase A was collected at a point 9 meters perpendicularly from the lower surface of contact. In macroscopic appearance and internal structure it is not markedly different from the normal gabbro. The essential minerals are hornblende and labradorite; the accessories, quartz, potash feldspar, titanite, magnetite. Zoisite, kaolin and much chlorite are the secondary constituents.

Chemical analysis of Phase A gave the following result:

SiO_2	52.94%
TiO_2	.73
Al_2O_3	14.22
Fe_2O_3	2.08
FeO	8.11
MnO	.35
MgO	6.99
CaO	10.92
Na_2O	1.40
K_2O	.49
H_2O below 110° C	.12
H_2O over 110° C	1.56
P_2O_5	.08
	99.99
Sp. Gr.	2.980

Analyst: Professor Dittrich.

The corresponding mineral composition in weight percentages is roughly as follows:

Hornblende	54.8%
Labradorite	25.6
Chlorite	11.0
Quartz	6.3
Titanite	2.0
Magnetite	.3
	100.0

On account of some alteration in the rock, it was found difficult to distinguish with certainty the small amount of alkaline feldspar; which has, accordingly, been entered in the total for labradorite.

At the perpendicular distance of 60 meters from the lower contact a related specimen was collected which may be called Phase A'. It is somewhat fresher than Phase A and gave the weight percentages thus:

Hornblende	42.9%
Quartz	22.8
Andesine	18.5
Biotite	6.6
Sodiferous orthoclase	5.5
Titanite	3.7
	100.0

The comparison of these two phases with the normal gabbro, Phase B, indicates the subordinate yet certain acidification of the sill-rock for at least 60 meters from the lower sill-contact. This lower contact zone thus tends to approach the intermediate rock, Phase C, in mineralogical and chemical constitution.

Résumé.

As a convenient summary of the foregoing description, the mineralogical and chemical analyses of the different phases have been assembled in Tables I. and II.

Table I.

Weight percentages of minerals as determined by the Rosiwal method.

	A	A'	B	C	D'	D	E
Hornblende	54.8	42.9	58.7	49.4	—	—	—
Biotite	—	6.6	.9	22.0	8.9	22.0	15.2
Labradorite, $Ab_1 An_1 — Ab_1 An_2$	25.6	—	34.8	—	—	—	—
Andesine, $Ab_4 An_3$	—	18.5	—	16.5	—	—	—
Oligoclase, $Ab_3 An_1$	—	—	—	—	1.5	1.5	1.0
Soda-bearing orthoclase . . .	—	5.5	—	—	24.9	29.1	32.5
Microperthite	—	—	—	—	—	—	3.9
Quartz	6.3	22.8	4.0	11.7	57.1	46.0	41.6
Muscovite	—	—	—	—	3.2	—	4.6
Apatite	—	—	.2	.3	—	.5	.2
Titanite	2.0	3.7	1.4	—	—	—	—
Magnetite	.3	—	—	.1	1.9	.5	1.0
Chlorite	11.0	—	—	—	—	—	—
Calcite	—	—	—	—	2.5	.4	—

The total is 100.0 in each case.

Phase A 9 meters from lower contact, Moyie Sill
» A' 60 meters » » » » »
» B Normal unacidified gabbro, equivalent of main mass of the Moyie Sill
» C Intermediate rock, 60 meters from upper contact, Moyie Sill
» D' Acid rock, 15 meters from upper contact, Moyie Sill
» D Acid rock, 12 meters » » » » »
» E Acid rock, 4.5 meters » » » » »

Phases A and A' belong to a lowermost zone of slight acidification. The basic Phase B constitutes the bulk of the sill. Next above the basic zone is a shallow zone of intermediate rock, Phase C, itself overlain by the fourth principal zone of highly acid rock represented by Phases D', D and E.

Corresponding to the foregoing tables, item for item, is the table of specific gravities (Table III.)

Table II.

Chemical analyses, Moyie Sill phases.

	A	B	C	D	E
SiO_2	52.94	51.92	52.63	72.42	71.69
TiO_2	.73	.83	.62	.68	.59
Al_2O_3	14.22	14.13	16.76	10.47	13.29
Fe_2O_3	2.08	2.97	2.86	.83	.83
FeO	8.11	6.92	10.74	5.50	4.23
MnO	.35	.14	.38	.16	.09
MgO	6.99	8.22	4.33	.41	1.28
CaO	10.92	11.53	6.17	2.53	1.66
Na_2O	1.40	1.38	1.41	1.93	2.48
K_2O	.49	.47	2.29	2.94	2.37
H_2O below 110° C	.12	.10	.12	.06	.14
H_2O over 110° C	1.56	1.07	1.17	1.11	1.31
P_2O_5	.08	.04	.33	.11	.07
CO_2	—	.06	.10	.61	.13
	99.99	99.78	99.91	99.76	100.16

Table III.

	Spec. Grav. (15° C.)
Phase E	2.773
» D	2.784
» D'	2.800
Average for granite zone, about	2.790
Phase C	3.020
» B, average about	3.025
» A'	2.967
» A (too low, as rock is altered somewhat)	2.980

Origin of the Acid Zone.

The critical point of the present paper is the explanation of this peculiarly stratified condition of the Moyie Sill. The question is synonymous with that of the origin of the acid zone. As for the main body of the igneous rock, there is little doubt that its intrusion occurred quite in the manner usual for basic intrusive sheets. It may be assumed from such facts as the great horizontal extent of the sill and, secondly, the ease of diffusion within the gabbro, that the basic magma was fluid at the time of intrusion. The fluidity may have been of a high order.

Among all the conceived hypotheses as to the origin of the acid zone, the writer has been forced to retain one as the best qualified to elucidate the facts in this one case of the Moyie Sill. More important still, this hypothesis better than any of the others, affords a coherent, fruitful and, it seems, satisfactory explanation of similar occurrences in other parts of the world. The view adopted includes what has been called "the assimilation-differentiation theory". The acid zone is thereby conceived as due to the digestion and assimilation of the acid sediments at both upper and lower contacts with the concomitant segregation of most of the assimilated material along the upper contact. The statement of the hypothesis naturally falls into two parts: — first, as to the evidences for assimilation; secondly, as to those favoring the special kind of differentiation involved.

Evidences for Assimilation.

1. Of primary importance in this connection is, of course, the composition of the sediments invaded by the original magma. One of the most noteworthy features of the huge series of conformable strata in the Creston-Kitchener series in this particular district is the marvellous homogeneity of the whole group. Hence it is that the study of comparatively few type specimens from these rocks can give a very tolerable idea of the average constitution of the quartzites. As already indicated, even the division into the two great sub-groups, Creston and Kitchener, is founded on but subordinate details of composition. Single beds typical of the Creston occur interleaved in the Kitchener and occasionally rusty beds are intercalated in the Creston series. In both series the average rock is a quartzite, always micaceous and often decidedly feldspathic. Many of the (Kitchener) strata immediately above

and below the Moyie Sill are seen, under the microscope, to have a composition essentially identical with that of typical Creston quartzite. It is, therefore, justifiable to use the chemical analysis of this latter rock in the attempt to evaluate the constitution of the sedimentary group invaded by the gabbro.

Professor Dittrich has analyzed such a type specimen collected several kilometers to the westward of the Moyie River. It is a very hard, light gray, fine-grained to compact, metamorphic sandstone breaking with a subconchoidal fracture and sonorous ring under the hammer. The hand-specimen shows glints of light reflected from the cleavage-faces of minute feldspars scattered through the dominant quartz. A faint greenish hue is given to the rock by the disseminated mica. This rock occurs in great thick-platy outcrops, the individual beds running from a meter to three meters or more in thickness. Occasionally a notable increase in dark mica and iron ore is seen in thin, darker-colored intercalations of quartzite. Ripple-marked surfaces are sometimes found, though they are not so common as in the overlying Kitchener quartzite.

In thin section this characteristic Creston quartzite is found to be chiefly composed of quartz, feldspar and mica, all interlocking in the manner usual with such old sandstones. The clastic form of the mineral grains has been largely lost during the regional metamorphism. The feldspars are orthoclase, microcline, microperthite, oligoclase and probably albite. The mica is biotite and muscovite, the latter either well developed in plates or occurring with shreddy, sericitic habit. The biotite is the more abundant of the two micas. Subordinate constituents are titanite in anhedra, with less abundant titaniferous magnetite and a few grains of epidote and zoisite.

The chemical analysis (Table IV., Col. 1) shows a notably high proportion of alkalies, and therewith the importance of the feldspathic constituents, especially of the albite molecule which alone holds about 15 °/₀ of the silica in combination.

Table IV.

	1.	2.	3.	4.	5.
SiO_2	82.10	76.90	74.23	79.50	72.05
TiO_2	.40	.35	.58	.38	.63
Al_2O_3	8.86	11.25	13.23	10.13	11.88
Fe_2O_3	.49	.69	.84	.59	.83
FeO	1.38	3.04	2.65	2.21	4.87
MnO	.03	.02	.07	.02	.12
MgO	.56	1.01	1.02	.78	.85
CaO	.82	.88	1.13	.85	2.10
SrO	—	—	Tr	—	—
Na_2O	2.51	3.28	2.78	2.89	2.20
K_2O	2.41	1.36	2.66	1.89	2.66
H_2O below 110° C	.05	.20	.08	.12	.10
H_2O above 110° C	.37	1.20	.81	.78	1.21
CO_2	—	Tr	.08	—	.37
P_2O_5	.04	.15	—	.02	.09
	100.02	100.33	100.16	100.16	99.96
Sp. Gr.	2.681	2.680	2.754	2.680	2.790

1. Type specimen of Creston Quartzite. Analyst: Prof. Dittrich
2. Type specimen of Kitchener Quartzite. Analyst: Mr. Connor
3. Specimen of Kitchener Quartzite from contact zone, Moyie Sill. Analyst: Prof. Dittrich
4. Average of analyses 1. and 2.
5. Average of analyses D and E, types of acid zone, Moyie Sill.

Mr. Connor has analyzed a specimen collected as a type of the Kitchener quartzite itself. It was taken from a point about 150 meters measured perpendicularly from the upper contact of the Moyie Sill and this specimen represents what appears to be the average quartzite both above and below the sill. The rock is rusty-brown on the natural outcrop and on joint-planes, but is light gray on the fresh fracture. It is rather thin-bedded, the thin individual strata being grouped in strong, thick plates sometimes rivalling in massiveness the beds of the Creston quarzite. Some cross-bedding and a few ripple-marks were observed.

The thin section discloses a fine-grained interlocking aggregate of quartz grains cemented with abundant grains of feldspar and mica. The feldspar is so far altered to kaolin and other secondary products that it is most difficult of accurate determination. One or two small grains only exhibit polysynthetic twinning and the preliminary study referred practically all the feldspar to the potash group. Mr. Connor's analysis shows conclusively, however, that soda feldspar is really dominant. The analysis was most carefully performed, the second complete determination of the alkalies agreeing very closely with the first. Supplementary optical study of the rock has pointed to the probability that pure albite as well as highly sodiferus orthoclase are present. Quartz makes up about 60°/₀ of the rock and feldspar from 25 to 30°/₀. Biotite both fresh and chloritized is the chief mica; sericite is here quite rare. Colorless epidote is the principal accessory; titanite, magnetite, apatite, a few zircons and pyrite crystals are the remaining constituents.

The analysis is given in Table IV., Col. 2. Col. 4 of the same table shows the average of Cols. 1. and 2. and may be taken as nearly representing the average chemical composition of the quartzite invaded by the Moyie Sill. This average may be at once compared with that of the two analyses from the granite zone of the sill, represented in Col. 5. The general similarity of the two averages is manifest. There is clear chemical proof that the greater proportion of the elements in the granite could have been derived directly by fusion of the quartzite.

That conclusion has been enforced by an examination of the exomorphic contact-zone at the upper limit of the sill. For the perpendicular distance of at least 20 meters from the upper surface of contact, the quartzite has been intensely metamorphosed. The rock is here vitreous, lightened in colour-tint, and exceedingly hard. Under the microscope the clastic structure is seen to have totally disappeared. Recrystallization is the rule. It takes the form of poikilitic or of micrographic intergrowth of quartz with various feldspars, along with the development of abundant well crystallized biotite and (less)muscovite. The feldspar is chiefly microperthite and orthoclase the latter often, perhaps always, sodiferous. Albite in independent, twinned grains of small size seems certainly determined by various optical tests. Innumerable, minute grains of zoisite and epidote occur as dust clouding the feldspars, micropegmatitic intergrowths, and even the quartz. Scattered anhedra of magnetite and small crystals of anatase and apatite are rather rare constituents.

The chemical analysis of this highly metamorphosed quartzite is entered in Col. 3., Table IV. In the preliminary study of the sill it was considered as probable that the quartzite had been somewhat feldspathized during the metamorphism, but the critical analyses seem hardly to bear out any certain conclusion on that point. The analysis shows that in several respects the metamorphosed rock is intermediate in composition between the granite of the sill and the unaltered quartzite. It should not be forgotten, however, that there is a perfectly sharp line of contact between the granite and this metamorphosed zone of the quartzite. The former rock has been in complete fusion; the latter rock still preserves its bedded structure.

The net result of the foregoing mineralogical and chemical comparisons affords good grounds for believing that the striking similarity of granite and quartzite is really due to a kind of consanguinity; that the igneous rock is due to the fusion of the sediment.

2. Granting that conclusion, there seems no other course open than to attribute the heat of fusion to the sill gabbro. A second test of the assimilation theory is suggested. This theory involves the assumption of sufficient heat to perform the work of fusion. It is, hence, an indication of great value that there is some acidification of the respective upper-contact zones in all of the six different sill-outcrops optically studied in the 85 kilometer stretch from Port Hill to Gateway; yet that this acidification is in

general in a direct proportion to the thickness of the sills. The Moyie Sill has at least four times the thickness of any other of the intrusive bodies. Presumably, therefore, its store of heat was much the greatest and its capacity for energetic contact-action much the largest. As a matter of fact, the Moyie Sill is the only sill bearing the truly granitic phase. The other sills are also somewhat more acid at their upper contacts than at their respective lower contacts, but the rock throughout is of gabbroid habit. The acidification in these cases has led to the development of abundant interstitial and poikilitic quartz, abundant biotite and less abundant alkaline feldspar in the hornblende-plagioclase rock. The rock of the acidified zones is here very similar to, if not identical with, the intermediate rock, Phase C, of the Moyie Sill. The acidification is relatively slight because these sills have been more rapidly chilled than the huge Moyie body. This point is based on deductive reasoning but it is no less positively in favour of the assimilation theory than the testimony of chemical comparison between the acid zone and the sediments.

3. There is, finally, direct field evidence that the Moyie gabbro has actually digested some of the quartzite. Along both the lower and upper contacts and, less often, within the main mass of the sill, fragments of the quartzite are to be found. These blocks have sharp contacts with the gabbro, but, none the less, they have the appearance of having suffered loss of volume through the solvent action of the magma. This phenomenon is quite familiar at intrusive contacts; its significance is only properly appreciated if one remembers that the visible effects of digestion are in but a small ratio to the total solvent effects wrought by the magma in its earlier, more energetic, because hotter, condition. It is not a violent assumption to consider that many quartzite blocks have thus been completely digested in the original gabbro magma. The product of this digestion is not now evenly disseminated through the crystallized gabbro, which except near its upper and lower contacts is very nearly identical in composition with the unacidified gabbro

occurring elsewhere in the district. No conclusion seems more probable than that the material of the dissolved blocks is now for the most part resident in the acid zone at the upper contact. The same view holds for the perhaps much more voluminous material dissolved by the magma at the main contacts themselves. The excess of acid material at the lower contact was held there because of the viscosity of the magma in its final, cooling stage. For the greater bulk of the digested material there has been, it appears, a vertical transfer upwards, a continuous cleansing of the foreign material from the basic magma.

The Differentiation.

In a word, there are reasons for concluding that the peculiar granitic zone at the top of the Moyie Sill is the immediate result of a special kind of differentiation, The composition of the original basic magma has been temporarily changed by the assimilation of quartzite; yet simultaneously gravitative adjustment has nearly restored the original composition, as the acid, assimilated material rose through the denser gabbro magma to the top of the sill. That the required differences of density were present is reasonably deduced from the specific gravities taken at critical points in the sill cross-section (Table III.) The table shows that the sill is quite systematically stratified in the sense required by this hypothesis. The crystallized phases of the sill show contrasts of density which undoubtedly existed in the final molten stage of the sill's history. (Cf American Journal of Science, Vol. XV., April, 1903, p. 279).

Yet the process of differentiation may not have been purely physical, i. e., due simply to density stratification. The granite seems to carry more ferrous iron and lime and probably a little more alumina than the average quartzite. By the simplest supposition the increase in these oxides is to be attributed to robbery from the original magma. The volume of the gabbro is so immense that its total constitution has been but slightly, perhaps quite indiscernibly, affected by such abstraction.

Tests of the Assimilation-Differentiation Hypothesis.

Apart from its intrinsic merits, the foregoing solution of the Moyie Sill problem should obviously be tested in two ways. Other explanations need valuation and comparison with that hypothesis. Secondly, if the solution is correct, it might be expected to explain other similar rock-occurences if any such exist and to undergo either rejection or corroboration as the hypothesis matches all the facts concerning those other examples.

Alternative Hypotheses.

The various possible suggestions as to the origin of the acid zone in the Moyie Sill include, besides the favoured one, the following:

a) The zone may be conceived to have been an independent intrusion, either younger or older than the gabbro. This view is negatived by the field relations. There is an entire absence of any clear-cut contact surface between the granite and gabbro which, on the contrary, are completely transitional to each other through the zone of intermediate rock. This intimate relation is of a different order from that sometimes observed in a belt of welding between two masses of successive igneous intrusion. That the intermediate rock is due to an interaction between gabbro and quartzite is plainly indicated by the existence of zones of similar rock along the contacts of the thinner sills where there is no intervention of a granite zone.

b) The acid zone may be conceived as due to the simple differentiation of matter originally injected as one thick sill; or

c) to the simple fusion and recrystallization of the quartzite (with or without assimilation by the gabbro magma) along the upper contact only.

These two latter hypotheses have been rather fully examined by the writer in the earlier note on the Moyie Sill. It is unnecessary to restate the grounds of their rejection which must be considered as yet more clearly advisable as those hypotheses are viewed in the light of the new information supplied by the chemical analyses. The strongest alternative view is, in the writer's opinion, that which attributes the granite-micropegmatite zone to contact fusion along the upper contact only. This view rests on the possibility that original magmatic waters were concentrated along the upper contact and, aided by the heat of the magma, could there specially favour the conversion of the quartzite into a local sheet of secondary magma. The chemical analyses seem to invalidate this hypothesis which is also subject to objection on account of the great rarity of quartz veins or other true mineral veins within the quartzite at the upper sill-contact. Nevertheless. the distribution of "juvenile" waters in intrusive magma offers an important field for investigation.

Other Illustrations.

Similarly, the more positive test of the assimilation-differentiation hypothesis, the witness of other examples in the world, especially those in Minnesota and Ontario, has been rather fully treated of in the former paper.

Summary.

A brief summing up of the whole case may, however, be of service in placing the hypothesis more clearly before the reader of the present sketch.

1. The Moyie intrusive is an enormously thick sill composed in greatest part of a peculiar hornblende gabbro slightly acidified at the lower contact. An equally abnormal biotite granite merging irregularly into micropegmatite forms a zone in the uppermost part of the sill, while a fourth zone of rock intermediate in composition between the granite and gabbro and, on the respective sides, transitional into those rocks, occurs between the thick basic zone and the much thinner granite zone.

2. The sedimentary formation cut by the sill comprises a very thick series of ancient sandstones highly quartzose but generally containing alkaline and soda-lime feldspars and always carrying mica.

3. At the time of intrusion the quartzitic strata lay flat.

4. At both contacts of the sill, the igneous rock contains foreign blocks shattered off from the quartzites. These blocks often show evidence of magmatic corrosion.

5. The field-relations and the chemical and optical study of sill-rocks and quartzites suggest that the material of the granite-micropegmatite zone is of derived origin. Most of that material resulted from the solvent action of the gabbro magma on the quartzite blocks and on the main sill-contacts. Some of the constituent elements of the granite may have been taken from the gabbro which, on account of its superior and great volume, shows no appreciable modification by such loss.

6. The asymmetry of the intrusive body is believed to be owing to the stratification of the sill by the action of gravitative adjustment. The product of assimilation whether at the lower main contact or about quartzite blocks immersed in the gabbro, possessed less density than the gabbro magma, rose through that magma and collected at the top of the sill. The intermediate rock represents a zone of incomplete differentiation.

7. The assimilation and concomitant differentiation are exhibited in other sills of the region, but, on account of the relatively small thickness and consequently smaller share of heat energy possessed by those sills, the action did not develop true granite.

8. Following the solidification of these sills, they were faulted and tilted to their present position in the fault-blocks of the Purcell Mountain Range.

9. More or less perfect parallels to the Moyie Sill have been described by various workers in Minnesota and Ontario. In all of these instances there is the same genetic relation of gabbro, granite and siliceous sediments or schists. An important special feature of the extraordinarily thick and extensive intrusive sheet of the Sudbury district in Ontario is an apparent case of the gravitative differentiation of the famous sulphide ores of that district.

General Application.

The Moyie Sill does not teach much that is absolutely new among the principles of petrology. The main purpose of the writer has been, on the other hand, to emphasize through the witness of an unusually well exposed example in nature, the importance of both magmatic assimilation and magmatic differentiation. The most significant single feature of the Moyie and neighboring sills as of the Minnesota and Ontario intrusives is their evidences of gravitative adjustment in magma. That is the most practical result of the investigation. If the principle is once thoroughly established, it must take a prominent place in petrological theory. This is true whatever be the origin of the magmas from which igneous rocks have been derived. The principle will evidently apply whether a magma were the compound product of assimilation by an earlier magma or whether it were the compound product of fusion through the rising of the isogeotherms in sediments, schists or ancient igneous terranes.

"In the foregoing discussion the secondary origin of certain granites has been deduced from the study of intrusive sills or sheets. It is clearly by no means necessary that the igneous rock body should have the sill form. The wider and more important question is immediately at hand: does the assimilation-differentiation theory apply to truly abyssal contacts? Do the granites of stocks and batholiths sometimes originate in a manner similar or analogous to that outlined for sills?" The writer has briefly noted general reasons affording affirmative answers to these questions. (Cf. American Journal of Science, Vol. XV., 1903, p. 269, Vol. XVI., 1903, p. 107).

"The difficulty of discussing these questions is largely owing to the absence of accessible lower contacts in the average granite body of large size. All the more valuable must be the information derived from intrusive sheets. The comparative rarity of such rock-relations as are described in this paper does not at all indicate that the corresponding petrogenic events are exceptional. It is manifest that extensive assimilation and differentiation can take place in sills only when the sills are thick, well buried, and originally of high temperature. All these conditions apply to the Moyie case. The phenomena described are relatively rare because thick basic sills cutting acid sediments are comparatively rare.

On the other hand, there are good reasons for believing that a subcrustal gabbroid magma, actually or potentially fluid, is general all around the earth; and, secondly, that the overlying solid rocks are, on the average, crystalline schists and sediments more acid than gabbro. Through local, though widespread and profound assimilation of those acid terranes by the gabbro, accompanied and followed by differentiation, the batholithic granites, syenites etc. may in large part have been derived. True batholiths of gabbro are uncommon, perhaps because batholithic intrusion is always dependent on assimilation.

The theory is applicable to plutonic rocks other than granite, to lavas as well as to intrusive bodies. Demonstration of the truth or error of the theory will doubtless be found in the study of intrusive igneous bodies rather than in the study of volcanoes either ancient or modern. Finally, the fact of "consanguinity" among the igneous rocks of a petrographical province may be due as much to assimilation as to differentiation."

~~Ha 704,2,16~~

[From The Amearican Journal of Science, Vol. XX, September, 1905.]

The SECONDARY ORIGIN of CERTAIN GRANITES.

By Reginald A. Daly, Ottawa, Canada.

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ART. XXIII.—*The Secondary Origin of Certain Granites;* by REGINALD A. DALY, Ottawa, Canada.

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- General Application.

General thesis of the paper.—Igneous rocks originate in magmas. The discovery of the laws governing the immediate derivation of such rocks from their parent magmas is, therefore, not the final aim of the geologist. He is logically compelled to refer rocks themselves to the yet more fundamental problem of the origin of igneous magmas. Whence come the raw materials of basalt, gabbro, porphyry or granite?

One of the earliest answers to this question has been gradually assuming a systematic statement in the form of the "assimilation theory". This theory holds that some igneous rocks are derived from the compound magmas formed by the local fusion of solid rock in molten rock of a different chemical composition. The process can be imitated in the laboratory furnace, and has certainly operated on many igneous contacts in nature. Yet one of the very latest utterances of one of the world's greatest petrologists reads thus: "The untenability of the 'assimilation' or fusion theory I regard as definitely proved."[*] On the other hand, a no less well known authority claims assimilation on a large scale as a necessary stage in the preparation of the Christiania granite.[†] Brögger and many of his followers hold that the contact phenomena of this granite show that the assimilation theory breaks down even when applied to a most favorable case.

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[*] "Die Unhaltbarkeit der 'Assimilations'- oder Einschmelzungs-Theorie betrachte ich als endgültig bewiesen."—J. H. L. Vogt, Die Silikatschmelzlösungen, Part II., Christiania, 1904, p. 225.

[†] F. Loewinson-Lessing, Comptes Rendus, 7th Session, International Geological Congress, 1899, p. 369.

This divergence of view is, of course, due to the lack of definite knowledge of the vital conditions controlling the activities of such an intrusive body as the Christiania granite. The study of its accessible contacts can, of itself alone, furnish neither proof nor disproof of the doctrine of wholesale assimilation. Without the aid of other geological data the attempt to solve the problem is like the attempt to produce graphically a complex curve of which but two points are known and fixed. Deep-seated assimilation about any magma chamber can only be finally discussed and evaluated if the complete form of the chamber and the complete composition of its rock-filling are at least tolerably known.

The present paper furnishes a brief discussion of a number of cases where it is believed that magmatic assimilation on a comparatively large scale has taken place. It is believed, further, that the geological conditions in these cases supply elements generally untouched in earlier discussions of the doctrine. The original magma had the composition of a gabbro intruded in the manner of sills; the invaded formations are ancient sandstones, both normal and feldspathic, with associated argillites or schists; the invaded formation, in every case, is more acid than the gabbro; the product of assimilation is always a granite graduating into granophyre. The acid magma is believed, however, to have been derived indirectly from the compound magma of assimilation through a systematic kind of differentiation. The primary cause of the differentiation is referred to the perfect or nearly perfect density stratification of each magmatic chamber.

The result of the investigation has been to confirm the writer's general theoretical conclusions on the subject of assimilation where it was necessarily introduced among the tests of the hypothesis of magmatic stoping*. Assimilation and differentiation are not antagonistic processes; both of them are involved in the secondary origin of some granites.

A. *The Sills of the British Columbia (International) Boundary.*

During the field season of 1904 the writer developed a geological structure section along the 49th parallel of latitude between Port Hill, Idaho, and Gateway, Montana, the two points where the Kootenay River crosses the boundary line between Canada and the United States. It was found that the mountains traversed by the section are for the most part composed of two very thick siliceous sedimentary formations which, in all probability, are of pre-Cambrian age. The two are conformable.

The lower formation has been called the Creston quartzite. It is a remarkably homogeneous, highly indurated light- to medium-gray sandstone, generally thick-platy in structure but occasionally interrupted by thin intercalations of argillaceous material. The formation is generally composed of nearly pure quartz with a little mica, but some bands are feldspathic to a notable extent. The total thickness of the formation is at least 9900 feet in the vicinity of Port Hill; its base was not directly observed.

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* This Journal, xv, 269, 1903, and xvi, 107, 1903.

Immediately overlying the Creston quartzite is the conformable Kitchener quartzite, composed of about 7400 feet of a highly ferruginous indurated sandstone. This formation is, in the field, distinguished from the Creston quartzite not only by the rusty color of the outcrops but also by a relatively thinner bedding and a greater proportion of micaceous cement, once somewhat argillaceous. Individual beds of the Kitchener quartzite are charged with detrital feldspar, but the formation as a whole is essentially composed of cemented quartz grains.

Dark-colored red, brown, and gray shales with thin intercalations of gray quartzite conformably overlie the Kitchener quartzite. The series, totalling 3200 feet in thickness, has been grouped under the name of the Moyie argillite. This formation appears but twice in the section and then only in comparatively small areas.

This great group of formations, from end to end of the section, has been mountain-built. A few open folds broken by faults appear in the eastern half of the belt, but the deformation has generally been due to the tilting of monoclinal blocks separated by strong normal faults and, more rarely, by thrusts. The tilting ranges though all angles up to verticality, but the average dip is less than forty-five degrees. In consequence of the deformation and subsequent denudation the edges of some 20,000 feet of well-bedded ancient sediment are now exposed for study. There have also come to light a number of thick sills of gabbro intruded at various horizons into the Kitchener quartzite and the upper part of the Creston quartzite. The intrusion and crystallization of the gabbro is believed to have taken place before the upturning of the sedimentaries. The faulting and tilting has repeated the outcrops of certain of the sills. One of the thickest of them has, along with the quartzites, been warped into one of the rare synclinal folds. The thickness of the sills varies from 100 feet to more than 2500 feet.

The main mass of each sill was uniformly found to consist of a hornblende gabbro with essential green (primary) hornblende and plagioclase (labradorite to anorthite, the latter in the cores of occasionally zoned feldspars). Accessory quartz, often in considerable amount, always accompanies the other accessories, which are titanite, titaniferous magnetite, and apatite with often a little biotite and sometimes a little orthoclase in addition. Epidote and chlorite are the principal secondary minerals. The structure of the rock is typically hypidiomorphic-granular.

Already in those sills that range from 400 to 500 feet in thickness, the gabbro is acidified near its upper contact. The change from the normal composition is seen in the great increase of biotite, orthoclase, microperthite and interstitial quartz.

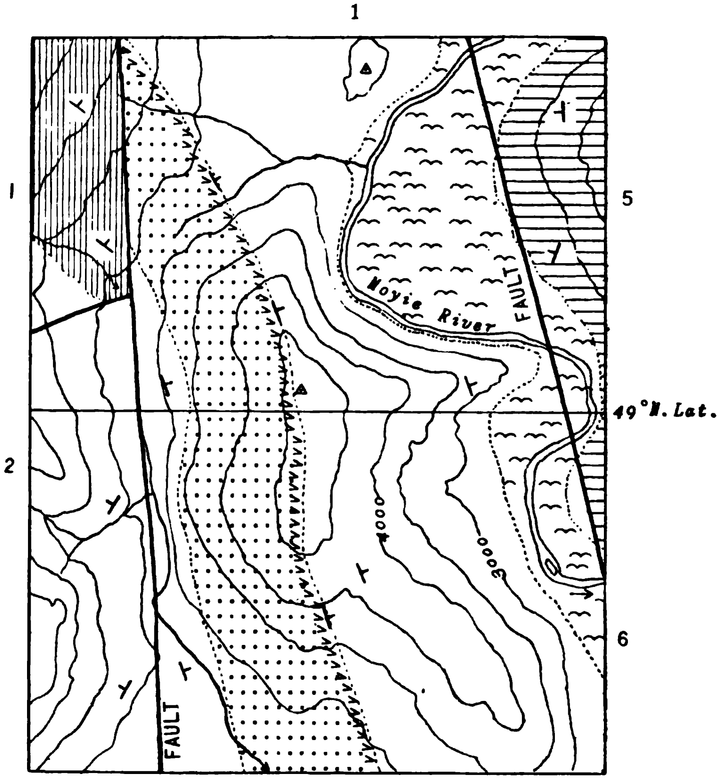

Fig. 1. Map of Moyie Sill, taken from plane-table sheet of the International Boundary Commission. 1. Moyie argillite. 2. Kitchener quartzite. 3. Hornblende gabbro sill. 4. Acidified (granite) zone of sill. 5. Creston quartzite. 6. Alluvium. Conventional sign for strike and dip. Scale: one inch = about one mile.

Biotite and quartz then assume the proportions of essential minerals. The quartz is characteristically in poikilitic relation to all the other constituents except orthoclase and microperthite, with which it is in true micrographic intergrowth. From this micropegmatite-bearing phase of the intrusive there is a gradual transition to the normal gabbro which thus composes the lower three-fourths or four-fifths of the sill.

The Moyie Sill.—The acidification of the upper zone of the gabbro being generally in a direct ratio to the strength of the sill, the phenomenon is specially marked in the greatest of all the intrusions. On account of its importance both in size and character, this rock-body is called the "Moyie Sill," the name referring to its situation on the Moyie River. A map and section of this sill are given in figs. 1 and 2, which illustrate one of the fault-blocks so characteristic of this part of the Boundary belt.* The sill is rather more than 2500 feet in thickness. It follows the bedding of the Kitchener quartzite, which here dips about sixty degrees to the eastward. The intrusive mass is seen to be cut off at its northern end by a master-fault which has dropped the Moyie argillite down into contact with the gabbro. This faulting is believed to have occurred after the sill-intrusion. There is a complete lack of contact metamorphism in the argillite where it adjoins the gabbro.

2

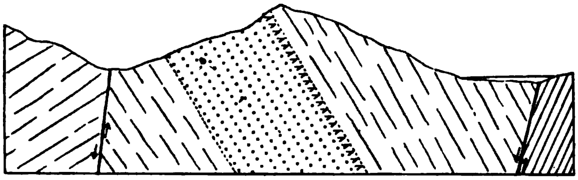

FIG. 2. Section of Moyie Sill, along line of the International Boundary.

Since the Moyie sill, throughout the six miles of linear outcrop studied, is in intrusive contact with the Kitchener quartzite alone, the other sedimentary formations need not here be described in detail. The Kitchener quartzite is, on the whole, a homogeneous terrane. On a fresh fracture the rock is seen to be a fine-grained, vitreous, light to darkish gray, well-bedded but tough, metamorphic sandstone, splitting with some readiness along the darker colored layers. The rusty color of the joint-surfaces and bedding planes is due to the leaching out and subsequent deposition of the iron contained in the pyrite, magnetite, etc., disseminated through the rock.

Under the microscope the rock is always seen to be essentially a fine-grained aggregate of interlocking quartz grains, seldom showing any direct traces of their detrital origin. The quartz mosaic is, in every thin section, shot through with abundant crystals of biotite which is often developed in phenocryst-like individuals occasionally as much as one centimeter in diameter. Sericitic muscovite is seldom absent as an essential, and sometimes rivals the biotite in abundance. Only rarely is feldspar essential; in one slide it seems to compose ten to fifteen per cent of the rock. So far as observed, the feldspar of the staple quartzite is orthoclase. No sodiferous mineral has been certainly determined in the rock. Epidote, zoisite, titanite, magnetite, leucoxene, pyrite and zircon, besides chlorite, secondary after biotite, are the other, always subordinate, constituents.

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* All the line-drawings used in illustration of this paper have been made for the most part by the aid of a typewriter, provided with a few special keys. The machine permits of a great saving of time in the preparation of the manuscript drawings. Cf. this Journal, vol. xix, 1905, p. 227.

In marked contrast to the normal quartzite is the rock collected at a point thirty feet from the upper contact of the Moyie sill. It is a very hard, vitreous, massive, light bluish gray quartzite carrying much feldspar. The whole rock seems to have been recrystallized. The granular-mosaic structure has been largely replaced by poikilitic and micrographic structures. Quartz is thus either regularly intergrown with feldspar or else encloses non-oriented individuals of the same mineral. The feldspar proved to be orthoclase, albite and microperthite, named in the order of their relative abundance. Biotite and sericitic muscovite are, as usual, in considerable amount. A little magnetite and a few minute crystals of anatase are the subordinate minerals. The characters of this contact phase point to the thorough metamorphism and notable feldspathization of the quartzite in the external contact zone of the gabbro.

The main mass of the sill-rock has the composition noted above as found in the sills generally. The grain is here medium to coarse, the structure hypidiomorphic-granular.

At the lower contact the grain of the gabbro is somewhat finer than in the interior of the sill, but the rock is still medium-grained and never compact. At the same time, interstitial and poikilitic quartz, along with biotite, orthoclase and microperthitic feldspar, are increased in amount. There is thus some acidification of the sill at its lower contact, though the rock is still gabbroid in macroscopic appearance and has hornblende and plagioclase (andesine to labradorite) as the chief constituents. Acidification of this order is visible for at least 200 feet from the lower contact. The intrusive rock is yet more abundantly charged with quartz, biotite and alkaline feldspars in the vicinity of the occasional xenoliths torn from the invaded quartzites.

The conditions are different at the upper contact. They may be readily studied on the wagon-road that threads the floor of the western meridional valley, shown in fig. 1. From the upper contact inward for a perpendicular distance of about 150 feet the intrusive is a highly siliceous rock, the mineralogical composition of which is shown in Table I and Table II. The structure of this rock varies irregularly, even in the same slide, from the hypidiomorphic granular of granite to the structure of granophyre or micropegmatite.

TABLE I.

Mineralogical composition of Rocks showing secondary derivation of Granite. (Essential minerals noted in italics.)

I. MOYIE SILL.

Gabbro.	Intermediate rock.	Granophyre-granite.
Hornblende	*Hornblende*	*Biotite*
Labradorite	*Biotite*	*Soda orthoclase*
Quartz	*Andesine*	*Microperthite*
Titanite	Quartz	*Micropegmatite*
Biotite	Chlorite	*Quartz*
Apatite	Titanite	Andesine
	Titanif. magnetite	Muscovite
	Apatite	Titanif. magnetite
		Apatite
		Calcite, epidote, kaolin

Country rocks: highly acid mica-bearing quartzite, sometimes slightly feldspathic, containing quartz, biotite and muscovite (sericite) as principal constituents, with orthoclase, epidote, titanite, magnetite, pyrite, zoisite, chlorite, leucoxene and zircon as subordinate minerals. Occasionally a thin layer or parting of more argillaceous composition.

II. PIGEON POINT.

Gabbro.	Intermediate rock.	Granophyre-granite.
Olivine	*Hornblende*	*Anorthoclase*
Diallagic augite	*Anorthoclase*	*Oligoclase*
Basic labradorite	*Plagioclase*	*Quartz*
Apatite	*Quartz*	*Micropegmatite*
Titanif. magnetite	Micropegmatite	*Chlorite*
	Chlorite	Augite (occasional)
	Magnetite	Muscovite
	Apatite	Rutile
	Rutile	Leucoxene
		Hematite
		Apatite

Country rocks: feldspathic quartzite and slate, containing quartz, orthoclase, plagioclase, chlorite, green mica, biotite, magnetite, leucoxene. Feldspar sometimes 75 per cent of the quartzite.

III. SUDBURY DISTRICT.

Norite.	Intermediate rock.	Granophyre-granite.
Hypersthene	*Hornblende* or *Hypersthene*	*Biotite*
Augite		*Orthoclase*
Bytownite	*Biotite*	*Micropegmatite*
Quartz	*Oligoclase-andesine*	*Microperthite*
Biotite	*Orthoclase*	*Microcline*
Hornblende	*Microperthite*	*Oligoclase*
Apatite	Quartz	*Quartz*
Magnetite	Epidote	Epidote
Sulphides	Apatite	Ilmenite
	Magnetite	Titanite

Country-rocks: sandstones, graywackes, slates, conglomerates, greenstones, volcanic tuffs and granitoid gneiss.

TABLE II.

Showing the weight percentages of minerals as determined by the Rosiwal method.*

	1.	2.	3.	4.	5.	6.	7.
Hornblende	58·7	54·8	42·9	49·4	...	...	...
Biotite	·9	...	6·6	22·0	8·9	22·0	15·2
Labradorite, Ab_1An_1–Ab_1An_2	34·8	25·6	...	...	...	...	...
Andesine, Ab_4An_3	...	...	18·5	16·5	...	...	...
Oligoclase, Ab_2An_1	...	...	...	...	1·5	1·5	1·0
Soda-bearing orthoclase	...	...	5·5	...	24·9	29·1	32·5
Microperthite	...	...	...	...	...	...	3·9
Quartz	4·0	6·3	22·8	11·7	57·1	46·0	41·6
Muscovite	...	...	...	...	3·2	...	4·6
Apatite	·2	...	...	·3	...	·5	·2
Titanite	1·4	2·0	3·7	...	...	...	...
Magnetite	...	·3	...	...	1·9	·5	1·0
Chlorite	...	11·0	...	...	...	...	...
Calcite	...	...	...	...	2·5	·4	...

Total is 100 in each case.

1. Normal unacidified gabbro from sill about eleven miles east of the Moyie sill.

Nos. 2 to 7 inclusive are types from the Moyie sill, specimens taken thus:

2. Thirty feet from lower contact.
3. Two hundred feet from lower contact.
4. Two hundred feet from upper contact.
5. Fifty feet from upper contact.
6. Forty feet from upper contact.
7. Fifteen feet from upper contact.

Table II was constructed by the use of the Rosiwal method for the determination of the relative quantities of the different constituents. The values are only approximate, owing to the difficulties of exact measurement and identification of the mineral grains. No account was taken of the sometimes abundant grains of epidote, occasional grains of calcite (measured in one instance), and often rather abundant scales of kaolin which occur in the slides. These minerals are products of the alteration of the feldspars, that alteration affording another difficulty in using the Rosiwal method for this suite of rocks. The proportions of the micas are probably too high on account of their not being even approximately equidimensional. Though these rocks do not lend themselves to a very satisfactory employment of the method, and though the table cannot be considered as accurate, the strong contrasts between the acid and basic phases of the sill are clearly evident.

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* Verh. Wien. Geol. Reichs-Anst., vol. xxxii, 1898, pp. 143 ff.

Since the compositions of the hornblende, biotite and soda-bearing orthoclase are not known, the chemical analyses cannot be calculated from Table II. Direct chemical analyses of types Nos. 1 and 7 in Table II have been made by Professor Dittrich, of Heidelberg, and are recorded in Table III.

TABLE III.

	1.	2.
SiO_2	51·92%	71·69%
TiO_2	·83	·59
Al_2O_3	14·13	13·29
Fe_2O_3	2·97	·83
FeO	6·92	4·23
MnO	·14	·09
MgO	8·22	1·28
CaO	11·53	1·66
Na_2O	1·38	2·48
K_2O	·47	2·37
H_2O (below 110° C.)	·10	·14
H_2O (above 110° C.)	1·07	1·31
P_2O_5	·04	·07
CO_2	·06	·13
	99·78	100·16
Sp. gr.	3·000	2·773

1. Normal unacidified gabbro from sill about eleven miles east of the Moyie sill.
2. Acid rock fifteen feet from upper contact of the Moyie sill.

The rock of col. 2 belongs to the granite family. The silica is normal (higher in types of cols. 5 and 6, Table II), but the total of the alkalies is extraordinarily low, namely 4·85 per cent, or ·76 per cent lower than the total of the potash and soda in the least alkaline among the twenty-six types of granite analyses selected for Rosenbusch's "Elemente der Gesteinslehre." The comparatively high content of lime is probably to be referred to a not unimportant mixture of lime feldspar and alkaline feldspar in isomorphous relation, as well as to a small amount of secondary epidote.

Col. 1 shows the gabbro to be a normal type in some respects, but the high content of silica and relatively low content of alumina and soda are abnormal for gabbro. These features are partly due to the predominance of hornblende over feldspar and to the presence of free quartz. It can be seen by inspection of cols. 1 and 2, Table II, that the gabbro at the bottom of the Moyie sill would give an analysis very close to that of col. 1, Table III, which represents a good type of the average gabbro from the many sills of the Boundary belt. A comparison of cols. 2, 4 and 7, Table II, shows that col. 4 corresponds to a rock-type intermediate between the two types actually analyzed. It is planned that a rather complete set of total analyses of the various phases of the Moyie sill will be published in the final report of the Chief Commissioner for Canada on Boundary Surveys.

Partially absorbed inclusions of the quartzite occur also in the upper, granitic zone of the intrusive.

Next to the peculiar granite-granophyre is a hundred-foot (thick) zone of intermediate rock which, with rapid transition, replaces the acid rock as the section is thus carried inwards through the sill. The mineralogical composition of this intermediate rock is shown in Tables I and II.

3

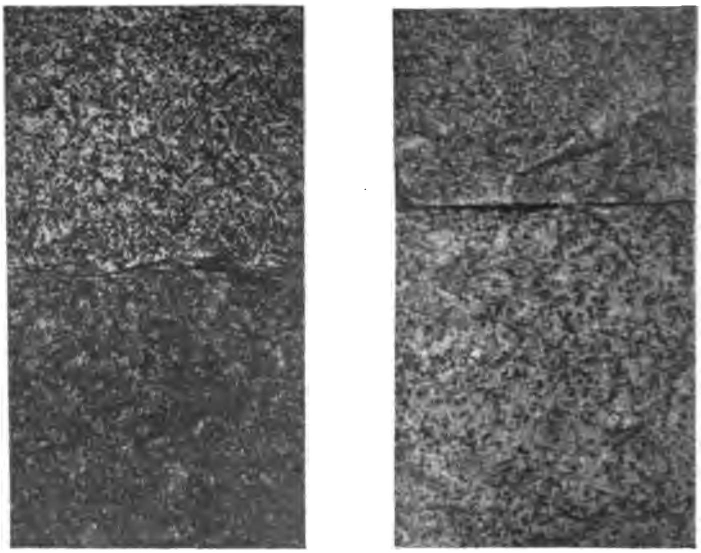

FIG. 3. Photograph of specimens showing contrast of color between a basic and a normal phase of the gabbro of the British Columbia sills and between both of these and two phases of the Moyie Sill granophyre-granite shown on the ~~left~~. right

The structure is again hypidiomorphic-granular with continual gradations into the granophyric. The grain varies from medium to rather coarse.

The intermediate rock grades imperceptibly into the normal gabbro of the internal part of the great intrusive body.

The variation in mineral composition among the zones of granite, intermediate rock and gabbro are shown in Table II.

The profound macroscopic differences of aspect are imperfectly illustrated in fig. 3, which shows the variation of color-tint. The corresponding variations in the specific gravity of specimens taken in the cross-section of the sill is shown in the following table:

Locality of specimen.	Sp. gr.
15 feet from upper contact	2·773
40 " " " "	2·784
50 " " " "	2·800
Average for granite zone about	2·790
200 feet from upper contact	3·020
Average for middle of sill about	3·025
200 feet from lower contact	2·967
30 feet " " "	2·980

A series of determinations showed in addition that the average specific gravity of the normal gabbro in all the sills of the Boundary belt is about 3·020.

Exomorphic contact action was observed at both upper and lower contacts with the Kitchener quartzite. It has taken the form of increasing the already high induration of the sediments with an accompanying special development of biotite at both upper and lower contacts. Though there is evidence of the feldspathization of the quartzite at the upper contact, none has yet been forthcoming for the lower contact, where, nevertheless, feldspar may have been similarly introduced from the magma. Doubtless on account of the chemical nature of the invaded sediments contact metamorphism is not conspicuous in the field, nor is it easy to trace its influence. The writer's impression is that the effects are more manifest, the action having been more intense, at the upper contact than at the lower, but additional field study will be required to test the real truth of that impression.

Apart from the development of exotic feldspar in the quartzite, indications of true pneumatolytic action seem to be lacking at both contacts. Mineral veins, including quartz veins, except occasional stringers of quartz, are conspicuously absent.

Field Hypothesis.—The hypothesis adopted in the field to explain these rocks and their relations involved a secondary origin for the granite-granophyre zone at the top of the sill. That zone was thereby interpreted as due to the contact-action of the gabbro intrusion on the adjacent Kitchener quartzite; digestion and assimilation of the sediments both on the main or "molar" contacts and on the peripheries of blocks shattered off from those contacts, was credited with the formation of a new compound magma from which the highly acid and somewhat anomalous granite was derived. The fact that the acid rock is practically confined to the upper contact-zone was explained by the collection of the products of digestion at the upper contact by gravitative adjustment in the magma. The low density of the locally formed new magma of assimilation would tend to effect its upward diffusion and the consequent cleansing of the heavier gabbro magma from such acid material. The comparatively slight acidification at the lower contact was attributed to the solution of the quartzite in the period immediately preceding the final consolidation of the sill; at that time the viscosity of the magma was too great to allow of the upward diffusion.

A principal test for such a hypothesis is obvious. If it be true, there should be other examples among the great basic sills cutting siliceous sediments. It has already been noted that there is actually such acidification of the other gabbro sills encountered between Port Hill and Gateway, and that in them the acidification is always most marked at the upper contact. Much more striking examples have been described with unusual thoroughness in Minnesota and Ontario. The comparison of these other cases is so important that the best established types will here be sketched and illustrated in some detail. The further discussion of the Moyie sill will be postponed to later pages, in which a synthetic treatment of all the examples will be undertaken.

B. *Occurrences in Minnesota.*

(*a*) The very able and specially detailed memoir of Bayley on the rocks of Pigeon Point contains, doubtless, the most elaborate argument in favor of the secondary origin of some granites. A brief summary of his facts and conclusions may well be given in the works of Bayley's own outline forming the introduction to his paper.

> "Pigeon Point is the northeastern extremity of Minnesota. It is one of a series of parallel points extending from Minnesota and Canada eastward into Lake Superior. Its backbone is a great east and west dike-like mass of a gray, coarse-grained rock that has always been called gabbro. This consists of phenocrysts of plagioclase in a diabasic groundmass of the same mineral, olivine and diallage, and consequently, it is a diabase porphyrite. . . . .
>
> "The rocks through which the gabbro cuts are evenly bedded slates and indurated sandstones of Animikie age. They dip south-southeast at 15 to 20 degrees, except at a very few places near the contact with other rocks, where they are more or less contorted. . . . .
>
> "The most interesting features in the geology of the point relate to the series of rocks usually occurring between the gabbro and the clastic beds. Beginning on the gabbro side the series

comprises in succession coarse-grained red rocks, a fine-grained red rock that is sometimes porphyritic and a well-marked belt of altered quartzites.

"The fine-grained red rock has all the characteristics of an eruptive. It sends dikes into the contiguous bedded rocks, and consists essentially of a hypidiomorphic granular aggregate of plagioclase, anorthoclase and quartz. The quartz and anorthoclase often form micropegmatite, while the plagioclase is in comparatively large grains, some of which have hardly defined idiomorphic outlines. At a few places this red rock is porphyritic, with bipyramidal quartz crystals imbedded in a red granophyric groundmass. The rock is similar to many of the augite-syenites described by Irving as occurring in the Keweenawan series, and is in structure and composition a quartz keratophyre.

"The coarse-grained rocks between the gabbro and the keratophyre are intermediate in character between these two. The variety nearest the gabbro differs but slightly from the basic eruptive. In addition to the gabbro components it contains a little quartz and red feldspar—constituents derived from the keratophyre. As the latter rock is approached, the augite, olivine, and plagioclase disappear, while increased quantities of quartz, red feldspar, and brown hornblende make their appearance, and the rock becomes more and more like the fine-grained red rock. Finally the hornblende disappears and the keratophyre is reached. Since the intermediate rocks occur only between the gabbro and the fine-grained red rock, and since all gradations in composition between the two end members of the series are represented, the coarse-grained red rocks are regarded as contact products formed by the intermingling of the gabbro and the keratophyre magmas."*

After describing the compound external zone of contact metamorphism, Bayley continues:

"From the above-mentioned facts it is concluded that the contact belt represents Animikie slates and quartzites that have been altered near their contact with an intrusive rock. The metamorphism of the quartzites has resulted simply in the recrystallization of the quartz and feldspar of the fragmental grains, with the addition, perhaps, of a little orthoclase.

"Since, in several instances, the gabbro is in direct contact with the metamorphosed rocks, while the keratophyre is not to be found in the neighborhood, it is inferred that the former rock and not the latter was the cause of the contact action."

The significant paragraph follows:

"Inclusions of fragmentals in the gabbro and the keratophyre have alike suffered the same alterations as have taken place in the various members of the contact belt, with this difference, that quartzite inclusions in the basic rock are often surrounded by a rim of red rock, identical in all its properties with the keratophyre. This suggests that the keratophyre itself may be of contact origin."

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* W. S. Bayley, Bull. 109, U. S. Geol. Survey, 1893, p. 11.

Finally:

"The conclusion reached is that, in all probability, the keratophyre is of contact origin—that is, it was produced by the fusion of the slates and quartzites of the Animikie through the action upon them of the 'gabbro.' The magma thus formed then acted in all respects like an intrusive magma. It penetrated the surrounding rocks in the form of dikes, and solidified as a soda-granite under certain circumstances, and under others as a quartz-keratophyre."*

4

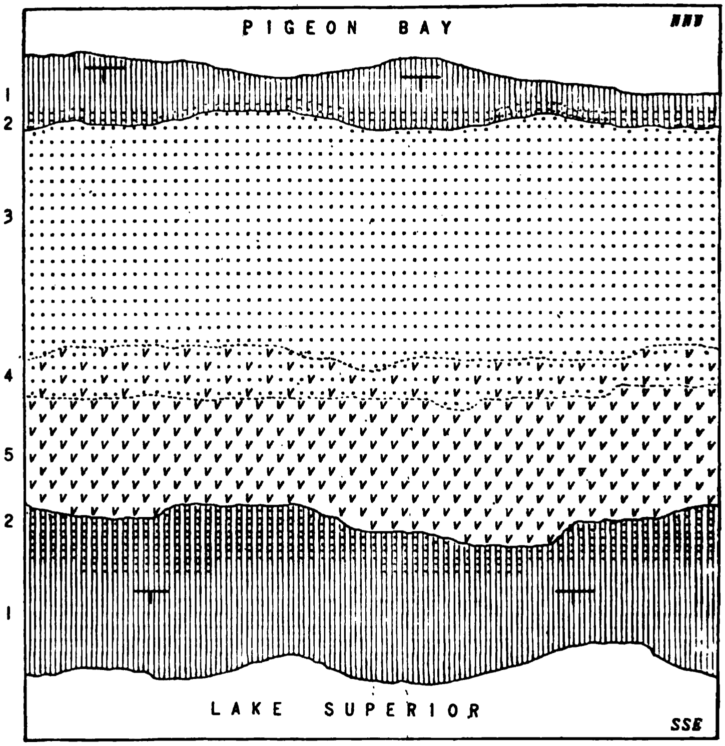

FIG. 4. Diagrammatic map of part of Pigeon Point, Minnesota, showing general relations among the different rock formations; after Bayley.

1. Animikie quartzites and slates. 2. Contact zone in the Animikie sedimentaries. 3. Olivine gabbro. 4. Intermediate rock. 5. Soda granite and keratophyre. Conventional sign for strike and dip. Scale: nine inches = one mile.

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*Op. cit., p. 12.

The diagrammatic map of fig. 4 generalizes the field relations as expressed in Bayley's maps. There have been omitted from the diagram certain complexities in the maps showing the actual geology. The essential features are thus made all the more evident; at the same time it is believed that this arbitrary treatment of the maps does not introduce error in principles.

A summary of the mineralogical compositions of the gabbro, intermediate rock, granite-keratophyre (granophyre) and invaded sediments is given in Table I. The correlative differences in chemical constitution are noted in Table IV.

TABLE IV.

Selected Analyses, Bayley on Pigeon Pt.

	A.	B.	C.	D.	E.	F.
SiO_2	49·88%	57·98	72·42	73·85	59·71	70·31
TiO_2	1·19	1·75	·40	·05	tr.	tr.
Al_2O_3	18·55	13·58	13·04	10·91	18·32	12·81
Fe_2O_3	2·06	3·11	·68	6·98	8·11	7·26
FeO	8·37	8·68	2·49	·89	·85	·88
MnO	·09	·13	·09	....	....	....
CaO	9·72	2·01	·66	·44	1·05	·60
BaO	·02	·04	·15	....	....	....
MgO	5·77	2·87	·58	1·52	3·54	2·03
K_2O	·68	3·44	4·97	1·39	3·43	1·90
Na_2O	2·59	3 56	3·44	2·28	1·93	2·19
H_2O	1·04	2·47	1·21	1·88	3·24	2·22
P_2O_5	·16	·29	·20	....	....	....
	100·12	99 91	100·33	100·19	100·18	100·20
Sp. gr.	2·923–2·970	circa 2·740	2·620	not given, prob. ca 2·70	not given, prob. ca 2·75	

A. Olivine diabase; aver. of five specimens	p. 37
B. Intermediate rock	63
C. Red granite; aver. of 7 specimens	56
D. Unaltered quartzites; aver. comp.	90
E. Unaltered slate	90
F. Approximation to aver. comp. of sediments	113

The general similarity in the character and spatial arrangement of the rocks at Pigeon Point and on the Moyie River is apparent. The comparison of conditions is obscure only as relates to the structural cross-section. The Moyie intrusive is unquestionably a sill. The underground relations of the Pigeon Point intrusive, for lack of decisive field evidence, have not been fixed beyond the possibility of doubt. Bayley says:

"The most prominent features of these gabbro masses are those of dikes. As has already been mentioned, the larger one [the one referred to in the present paper] in many places presents perpendicular walls both to the north and to the south. It occupies all the highest portions of the point, and these are in a straight line. It has the appearance of an intrusive mass, and is like any one of those forming the numerous points to the north of the international boundary line. It has been regarded as a dike by both Irving and N. H. Winchell. Its contact with the sedimentary rocks is only occasionally to be seen. At several of these contacts the eruptive has the appearance of having escaped from between the dike walls and thrust itself for a short distance between the fragmental beds, or having piled itself up around the dike orifice and overlapped the intruded rocks. . . . . At only two places on the north shore do the fragmental rocks appear, and at these places they are far below where they should be were they interbedded with the gabbro, and in neither case is the contact like that of interbedded eruptive and sedimentary rocks."

He concludes that:

"The larger mass of the Pigeon Point gabbro is in the form of a dike, which has broken through its walls at certain places and intruded itself between the strata of the surrounding rocks."*

In accordance with his view Bayley's cross-sections show vertical contacts among all the igneous rock members and also between sediments and eruptives.

On the other hand, Professor N. H. Winchell states, in a personal letter to the writer:

"All my observations bearing on the relations of the gabbro to the Animikie on Pigeon Point lead to the conclusion that the gabbro is later than the Animikie. But the term gabbro here is made to include those coarse non-ophitic dikes that resemble gabbro and which are also allied to diabase. There are abundant places where this rock is in the form of sills in the Animikie. The great backbone of Pigeon Point, which is the most distinctly gabbroid of the intrusive rocks, is simply a large example of a sill, while, as I interpret the structure, many of the dikes cutting the Animikie are only contemporary offshoots from it."

With Winchell's view there agrees the observation of Bayley that the feldspar phenocrysts of the porphyritic gabbro are sometimes "arranged in rude layers parallel to the dip surfaces of the quartzite. Their longer axes are usually in the direction of the dip of the sedimentary rocks."† This orientation suggests flow-structure parallel to contacts. Professor Bayley has, by letter, restated to the writer his conclusion that "the gabbro was intruded as a boss or huge dike, certainly not as a sill," but adds the remark that "while the contacts of the quartzites with the red rock and gabbro so far as they were seen are vertical, it does not necessarily follow that they are vertical with depth." He continues: "I have no means of knowing the date of the intrusion. With respect to the tilting (of the quartzites) my guess is that the intrusion was prior to the latest tilting, but later than an earlier tilting lakeward."

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* Op. cit., pp. 22–23.

† Op. cit., p. 23.

The possibility that the Pigeon Point eruptive is either a true sill only locally breaking across the bedding of the sediments or at any rate dips as a whole to the south-southeastward, is further suggested by the analogy of the many undoubted sills of gabbro cutting the southerly to southeasterly dipping Animikie of Minnesota. Some of these sills have likewise zones of soda granite lying between the gabbro and the sediments on the southerly flank of the gabbro. Thus in those cases the sediments dip under the gabbro on the one side of the eruptive body and away from the granite on the other side.

Bayley's full and trenchant argument for the contact origin of the soda granite and granophyre need not be repeated. The independent origin of the acid rock is rendered highly improbable by the occurrences of the intermediate rock lying directly between the gabbro and the sediments without the intervention of the true granite or granophyre.

The efficiency of contact-shattering in aiding the digestion of the slates and quartzites is strikingly manifest in Bayley's descriptions.

"Very close to the red rock appears a belt in which the various rocks are in the most complicated relations imaginable. In the eastern portion of the point this belt is well seen on the southern shore, about one-third of a mile from the end of the point. (See Pl. XVI.) Here the red rock is exposed in low cliffs, and in it are small, sharp slate and quartzite inclusions, into which the red rock penetrates in every direction. The exact line of contact between the red rock and the bedded fragmentals cannot be detected, as they appear to merge gradually into one another, the latter becoming redder and redder as they approach the former, which penetrates them in veins and dikes, and finally includes numerous pieces in such a way as to yield a good eruptive breccia."

"Some of the inclusions are very sharp and but little altered, while others are partially dissolved, and are surrounded by concentric zones, resulting from the action of the red rock upon the material of the inclusion, and the reciprocal effect of the partially dissolved inclusion upon that portion of the red-rock magma immediately contiguous to it. . . . . Thus it would seem to be a fact beyond controversy that the red rock is the immediate cause of the alteration noticed in the fragmental rocks and of the breccia observed along its contact with them. If, however, the contact belt is examined very closely, it is found that although the red rock is always accompanied by a zone of this belt, there are localities in which the latter occurs without the presence of the former. . . . . The metamorphosing rock seems to be the gabbro. Just as in the case of the contacts with the red rock, the quartzites become mottled as they approach the eruptive, and inclusions of the former in the latter are so frequent that there appears to be a gradual transition between the two rocks."*

Similar shatter-breccias are described at the northern contact. The metamorphism of the inclusions is there the same in kind as on the southern contact but is less intense.†

(*b*) A significant discovery was made at a mining prospect on Governor's Island just south of Pigeon Point. The shaft started in hardened slate at the surface, then struck red quartzite and finally red granite where the sinking was discontinued. In this case there is no question that the sediments overlie the granite in a relation similar to that involved in the sill theory of the Pigeon Point intrusive.‡

(*c*) Parallels to the Pigeon Point case have also been found on Spar, Jarvis and Victoria Islands.§ Lawson has described other examples among the Logan sills of Lake Superior, and says that the sills are repeated by step-faults gently tilting the sills to the southeast at the maximum angle of five degrees.‖

(*d*) Grant describes the great gabbro area of Cook County, Minnesota, as a laccolith in the gently dipping Animikie quartzites, slates and graywackes. He maps soda granites passing into alkaline quartz porphyries on the southern flank of the gabbro or in it. This latter occurrence is possibly to be related to the occasional horizontal dips of the Animikie.¶

N. H. Winchell maps a broad band of the red granite to the southward of the huge gabbro mass of Lake County. He states that the southern limit of the gabbro forms the northern limit of the red granite, but that there are numerous places where these rocks are intricately interbedded and in some instances isolated areas of the red rock are surrounded by gabbro.** The official atlas of the Minnesota Geological Survey indicates still other large-scale examples of the same or similar close relations of gabbro and red granite—notably those mapped in vol. vi, plates 68, 69, 84, 85 and 87.

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* Op. cit., pp. 28–29. † Op. cit., p. 81.

‡ Final Report, Geol. Surv. of Minnesota, vol. iv, 1899, p. 516, and vol. v. 900, p. 799.

§ Bayley, op. cit., p. 30; cf. E. D. Ingall, Ann. Rep. Geol. Surv. Canada, 1888, Pt. H, pp. 45 and 49.

‖ Bull. 8, Geol. Surv. Minnesota, 1893, pp. 30–33–42–44.

¶ Final Rep. Minn. Geol. Surv., vol. iv, 1899, pp. 323 and 326.

** Ibid., pp. 296–7.

C. *The Sudbury Intrusive Sheet.*

A still more remarkable parallel to the conditions of the Moyie sill has been rather fully described by Barlow and Coleman, following the earlier work of Walker in their respective memoirs on the geology of the Sudbury District, Ontario. In the scale of the various related phenomena, in the wonderfully systematic arrangement of the different rock-formations, and in the occurrence of valuable ore-bodies directly and genetically associated with the intrusive, the Sudbury District example stands unique in petrographical records.

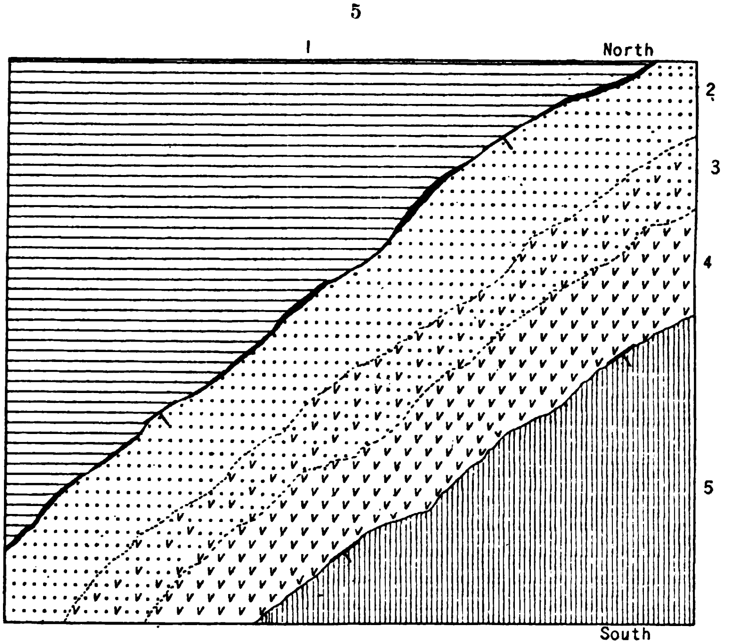

FIG. 5. Diagrammatic map of part of the Northern Nickel Range, Sudbury District, Ontario; after Coleman.

1. Granitoid gneiss, greenstones and graywackes. 2. Norite. 3. Intermediate rock, transitional between norite and micropegmatite. 4. Micropegmatite. 5. Slates, sandstones and volcanic tuffs. (The position of the sulphide ores shown by heavy black line.) Conventional sign for strike and dip. Scale: one inch = two miles.

The latest reports of Barlow and Coleman agree in the conclusion that the famous nickel-bearing eruptive has the form of an enormous intrusive sill of a composition exactly analogous to that of the Moyie sill excepting as regards the development of the valuable sulphides. It is "a vast sheet of eruptive rock having a basin shape; a sheet nearly 40 miles long and 17 miles wide, and probably a mile and half to two miles thick on the average, if the (average centripetal) dip (of the sheet) is 45 degrees."*

This great sheet cuts sediments and schists referred to the Laurentian and Upper Huronian. Their general field relations are summarized in the diagrammatic map of fig. 5, drawn from a part of Coleman's official map of the "Northern Nickel Range." Again the gabbroid rock (norite) is seen to be concentrated on the lower contact of the sheet, the acid rock, micropegmatite or granophyre, graduating into true granite, on its upper contact, while between the two is a zone of intermediate rock. On the "Southern Nickel Range" across the spoon-shaped basin, Barlow has determined the same arrangement of acid, intermediate and basic zones in the sheet, which there, however, agreeably with the basin theory of structure, has a northerly dip; so that in this case, the norite occurs on the south side of the sheet, the granite-granophyre zone on its northern side. On the basin theory of the structure, the volume of the granite-granophyre in this sheet is to be measured by hundreds of cubic miles.

All around the basin the nickel ores form a more or less continuous zone at the lower contact of the norite. The sulphides are also to be found in especial abundance as segregations in apophysal offshoots of the norite where the basic magma penetrated fissures outside the lower contact of the sheet.

Coleman states that where the band of eruptive (outcrop edge of the sheet) is narrow, there is less change in the rock in passing from the lower to the upper contact, the most basic norite as well as ore being absent for the most part. He also notes the absence of granophyre or granite in the smaller intrusions of the norite which occasionally appear outside the main basin.†

Eruptive breccias due to the shattering of the invaded formations by the hot magma are found at both upper and lower contacts.‡

Coleman notes that in the northern nickel range the contact metamorphism is more intense next the upper acid zone than next the norite. He explains this as possibly due to the fact that the rocks at the lower contact were already well crystallized before the intrusion took place, while the sediments along the upper contact were then capable of notable mineralogical changes. The metamorphism on the upper contact extends outward for a distance of from 1000 to 1500 feet.

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* A. P. Coleman, Rep. Bureau of Mines, Ontario, 1903, p. 277. Cf. A. E. Barlow, Ann. Rep. Geol. Surv. Canada, vol. xiv, 1904, p. 72; also stereogram accompanying Coleman's report.

† 1904 report, p. 212, and 1903 report, p. 286.

‡ A. E. Barlow, op. cit., pp. 122, 129 and plates; A. P. Coleman, Rep. Bureau of Mines, Ontario, 1904, p. 213; T. L. Walker, Quart. Jour. Geol. Soc., vol. liii, 1897, p. 54.

There seems to be a decided lack of pneumatolytic action (other than that due to water vapor) incident to the intrusion.*

Coleman has concluded that the intrusion of the sheets *antedated* the synclinal warping of the region to which the present basin shape of the sheet is attributed.†

The mineralogical compositions of the norite, intermediate rock and micropegmatite-granite are summarized in Table I. Their chemical compositions are entered in Table V, taken from Walker's paper, page 56. The corresponding specific gravities also show the significant homologies existing between these rocks and those of Pigeon Point and of the Moyie sill. The value of a close study of these tables will appear in the following general comparison of the rocks and of their relations to one another.

TABLE V.

	1.	2.	3.	4.	5.
SiO_2	49·90%	51·52%	64·85%	69·27%	67·76%
TiO_2	1·47	1·39	----	·78	·46
Al_2O_3	16·32	19·77	11·44	12·56	14·00
Fe_2O_3	----	·47	2·94	2·89	----
FeO	13·54	6·77	6·02	4·51	5·18
MgO	6·22	6·49	1·60	·91	1·00
CaO	6·58	8·16	3·49	1·44	4·28
Na_2O	1·82	2·66	3·92	3·12	5·22
K_2O	2·25	·70	3·02	3·05	1·19
H_2O	·76	1·68	·78	·76	1·01
P_2O_5	·17	·10	·24	·06	·19
	99·03	99·71	98·30	99·35	100·29
Sp. gr.	3·026	2·832	2·788	2·724	2·709

1 to 5—"Specimens range from north to south" across the Sudbury intrusive sheet, that is, from near lower contact (No. 1) to near upper contact (No. 5).

Synthetic Discussion.

Magmatic Assimilation.—The secondary origin of granite has long been maintained by N. H. Winchell, who has referred to the Pigeon Point case as, among others, demonstrating the fact.‡ Bayley came to the same belief for the granite and granophyre of the point, but did not extend his argument in detail to cover other occurrences among the Minnesota intrusives. On the other hand, the principle has not been accepted as applying to these localities even by Van Hise, whose rare knowledge of Lake Superior geology must give his opinion exceptional weight.* Even the latest text-books of geology give most inadequate treatment of the doctrine though it refers to one of the most important problems in the whole field of geology. Doubtless the majority of petrologists are to-day unfavorable to the assimilation theory of granite and its relatives except as it applies to a very limited, in point of volume insignificant, modification of certain magmas at their contacts.

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* A. E. Barlow, op. cit., p. 129.

† 1903 report, p. 277.

‡ Final Rep. Minn. Geol. Surv., vol. v, 1900, p. 62, etc.

Van Hise's chief argument against the contact origin of the Pigeon Point granite emphasizes the fact that that rock has not the chemical composition either of the sedimentary formation or (as especially shown in the surplus of alkalies and the deficiency of iron in the granophyre-granite) of a direct mixture of gabbro and sediments.† The much quoted argument of Brögger with reference to the Norwegian granites is based on a similar fact.‡ Many other writers have, on a similar ground, excluded contact assimilation as playing any considerable part in the formation of abyssal or hypabyssal magmas.

In practically every case the opponents of the assimilation theory have treated of the assimilation as essentially a static phenomenon. Each interpretation of field facts has been phrased in terms of magmatic differentiation *versus* magmatic assimilation as explaining the eruptive rocks actually seen on the contacts discussed. Nothing seems more probable, however, than that such rocks are often to be referred to the compound process of assimilation accompanied and followed by magmatic differentiation. The chemical composition of an intrusive rock at a contact of magmatic assimilation is thus not simply the direct product of digestion. It is the net result of rearrangements brought about in the compound magma of assimilation. In the magma, intrusion currents, convection currents and the currents set up by the sinking or rising of xenoliths must take a part in destroying any simple relation between the chemical constitutions of the intrusive and invaded formations. Still more effective may be the laws of differentiation in a magma made heterogeneous by the absorption of foreign material which is itself generally heterogeneous. The formation of eutectic compounds or mixtures, the development of density stratification, and other causes for the chemical and physical resorting of materials in the new magma ought certainly to be regarded as of powerful effect in the same sense.

A second fundamental principle has as a rule been disregarded in the discussions on magmatic assimilation. The *form* of the intrusive body, and the relation of the accessible points of its contacts to that form as a whole, must be taken into account. If, for example, differentiation of the compound magma has taken place so as to produce within the magma chamber layers of magma of different density, the lightest at the top, the heaviest at the bottom, the actual chemical composition of the resulting rock at any contact will depend directly on the magmatic stratum rather than on the composition of the adjacent country-rocks.

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* Monograph XLVII, U. S. Geol. Surv., 1904, pp. 730–733.

† Op. cit., p. 733.

‡ Die Eruptivgesteine des Kristianiagebietes, Pt. II, 1895, p. 130.

Thirdly, the method of intrusion is of primary significance in the discussion of assimilation in a given instance. There are strong reasons for believing that the subterranean chambers of stocks and batholiths have been opened largely or at least in part through magmatic "stoping," whereby magmas have made their way upward through the invaded formations by engulfing suite after suite of blocks shattered off from those formations by the heat of the intrusives.* In such a case the destructive action at the molar contact is chiefly physical, and chemical solution is subordinate. Most of the solution takes place in the complete digestion of the sunken blocks and is therefore abyssal rather than marginal. The conditions are peculiarly favorable for the systematic differentiation of the new compound magma. The chemical composition of the intrusive at any contact will thus depend on the constitution of a (possibly well differentiated) magma containing materials won from *all* the invaded formations and not simply materials won from the immediately adjacent country-rock. Brögger's argument derived from the low content of lime in the Christiania granite cutting thick limestones (themselves overlying an enormous thickness of crystalline schists, etc.) is clearly inconclusive until it can be shown that this and the other two factors just noted have not been at work.†

Magmatic stoping has, in all probability, taken place to some extent in the great intrusive body at Pigeon Point. The specific gravity of the gabbro varies from 2·923 to 2·970. Molten at 1400 degrees Cent., its specific gravity, at atmospheric pressure, would be not far from 2·43 to 2·48. The specific gravities of the intermediate rock and granite are respectively 2·740 and 2 620; molten at 1400 degrees Cent., they would, at atmospheric pressure, be about 2·30 and 2·19 respectively. The specific gravity of the invaded sediment varies from 2·70 to about 2·75. Blocks of the quartzite and slate immersed in any of the molten magmas and there assuming the temperature of 1400 degrees Cent., would at the same pressure have specific gravities varying between 2·60 and 2·65. There are good reasons for believing that plutonic pressures would not essentially affect these contrasts of density. Assuming a certain degree of fluidity in the magma (an assumption underlying the whole of this paper and believed to be demonstrated by such facts as the patent ease of diffusion that once reigned in each of the intrusives), it appears that blocks of the sedimentary rocks must sink in the magma, whether acid or basic.*

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* Cf. R. A. Daly, The Mechanics of Igneous Intrusion, this Journal, vol. xv, 1903, p. 269, and vol. xvi, 1903, p. 107.

† Cf. Loewinson-Lessing, op. cit., p. 368.

The actual shatter-breccias described by Bayley are therefore to be attributed to the last destructive effort of the magma, which, at that time, through cooling, had become too viscous to allow of the sinking of the xenoliths.

A precisely similar argument applies to the Moyie and Sudbury examples (see table of specific gravities and table in this Journal, vol. xv, 1903, p. 277). All these igneous bodies, though not intruded by magmatic stoping, yet show that process to have assisted in the production of the granites and granophyres. Whether this process has there been more or less efficaceous than molar or marginal assimilation, perhaps cannot be determined.

In all these cases the stoping that did occur must clearly have tended to destroy a simple chemical identity between igneous rock and country-rock at any given contact.

Summary.—It will be useful to review the chief field and laboratory observations so far noted as favoring the assimilation theory when applied to the granites and granophyres described in this paper.

1. Bayley's elaborate argument is believed to be valid except as it fails to take differentiation into account. No fact has been noted either by the writer in connection with the Moyie sill or in the descriptions of the other examples which tends to weaken that argument.

2. Belief in the truth of his conclusion is greatly strengthened by the repeated occurrence of essentially the same phenomena in widely separated regions.

a. At Pigeon Point, at Sudbury and on the Moyie River there occur intrusive bodies of gabbro passing by gradual transitions (as shown by chemical, mineralogical and specific gravity determinations) into the border phases of granite and granophyre. Both types of rock clearly belong to the same period of intrusion.

b. All three igneous bodies are of relatively great thickness, which means that, other things being equal, they possessed relatively great stores of thermal energy.

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*Cf. R. A. Daly, op. cit., 1903, p. 277, etc.

c. In each occurrence the gabbro contains xenoliths of the more acid sedimentary rocks. These blocks are commonly more or less digested and the product of this local solution is always closely allied to, if not equivalent to, the granophyre-granite phase.

d. In each case there is correspondence though not equivalence between the composition of the acid border-phase and the average composition of the invaded formation. This important fact is emphasized in Tables I, II, III, IV and V, in which the silica and alkalies are either directly or inferentially seen to be more or less abundant in the granophyre-granite according to the relative abundance of those oxides in the respective country-rocks.

e. A considerable number of other examples not as yet thoroughly studied have been noted in British Columbia and Minnesota. The conditions are throughout identical or so allied as to favor one explanation common to all the occurrences.

f. The assimilation theory is also supported by certain other facts which have already been mentioned but merit a more detailed discussion such as is attempted in the sequel.

3. The principal objection to the doctrine of assimilation, namely, the objection that chemical analyses disprove any genetic relationship between intrusive and invaded formation at certain accessible contacts, cannot hold, because that objection allows no place for differentiation in the magma made compound by assimilation.

Asymmetry of the Intrusive Bodies.—There remains for particular explanation the cardinal fact that all the intrusive bodies are asymmetric. The granophyre-granite is always concentrated on one side of the intrusive, that is, along the upper contact or the side away from which the enclosing sediments dip.

In all the localities the dips of the sedimentaries and of the intrusive sheets are believed to have been flatter at the time of the injection of the magma than those dips now are. It is, indeed, possible that, in every instance, the gabbro sheet lay practically horizontal during the period of cooling and consolidation. In any case the granophyre-granites appears to have always overlain their respective gabbroid associates.

Three possible explanations have offered themselves for this asymmetry. (*a*) It is conceivable that extensive assimilation occurred only on the upper contacts; or (*b*) the asymmetry may be due to the density stratification of magma compounded of gabbro and digested sediments; or (*c*) due to a combination of both those factors.

One or more subordinate suppositions are necessary if the assimilation be credited essentially to the upper contact. On the one hand, the invaded formations above and below the gabbro might be lithologically so different that the one above was much more subject to contact alteration than the one below. This idea is at once declared irrelevant in the British Columbia and Minnesota cases, where there is certainly no evidence of differences of digestibility.

On the other hand, it is possible that the original gabbro was differently constituted, and thus more energetic in assimilation, along the upper contact than elsewhere. Magmatic water or other strong solvents may thus be conceived to have early concentrated in the upper zone of each sill. In favor of this view would seem at first sight the fact that at Pigeon Point the zone of external metamorphism is reported by Bayley to be much wider on the upper contact than on the lower. (See fig. 4.) The same seems to be true in the Sudbury case, but is explained by Coleman as noted on a previous page. The writer could find no absolutely certain evidence of such differential metamorphism about the Moyie sill, yet considers it as probable.

That the conditions for the complete assimilation of the invaded formations obtained throughout the intrusive bodies is illustrated in the unmistakable digestion of xenoliths found at all depths in the gabbro. As already pointed out, the assimilation here belongs to the period immediately preceding the consolidation of the gabbro. A much greater volume of similar material derived from the interaction of gabbro and sedimentary rock must have been formed from other blocks in the hotter, more fluid, and more energetic magma of the preceding period. There seems to be no possible doubt that most of that material has diffused upward and now forms part of the granophyre-granite zone.

The simplest and most probable cause for that diffusion is, as suggested in the field hypothesis for the Moyie sill, the difference of density between the acid magma of assimilation and the enclosing gabbro.

It is quite possible that the metamorphosing effect of the new magma may have been greater than that of the original pure gabbro. The new magma would presumably carry with it the water derived from the digested sediments which, apparently in every case, are notably more hydrous than the original gabbro magma. The accompanying table shows the proportion of water (or loss on ignition) found in the analyses of the rocks of Pigeon Point.

Rock.	Per cent of water.
Gabbro	1·04
Intermediate rock	2·47
Red soda granite	1·21
Slate	3·24
Quartzite (loss on ignition)	1·88

So far as such water determinations in the crystallized rock can be considered as indicating a true condition of the magma before solidification, the table implies that the compound magma corresponding to the "intermediate rock" still held the extra water of assimilation up to the moment of crystallization; and, secondly, that the well differentiated magma corresponding to the soda granite had lost about half of the water of assimilation before final solidification. It is, accordingly, quite possible that this extra water which the upper acid zone could not hold in permanent combination, has been responsible for the unusual amount of external metamorphism in the sediments south of the Pigeon Point intrusive. Similar reasoning may apply to the Sudbury example, but the required elaborate chemical study of its more complex terranes has not yet been made.

In favor of this hypothesis is the fact that, so far as known to the writer, differential contact metamorphism of the kind here in discussion has never been described in connection with a sill that does not also show evidence of strong internal assimilation.

Finally, there is no cause yet well determined why water or other solvents should be systematically concentrated from the original magma along the roof of an intrusive sill. Such concentration may, indeed, be the rule, but it has apparently not been announced by any worker among the thousands of basic sills described in geological literature.

The conclusion seems justified that the special intensity of the metamorphism on the upper contact of certain intrusive bodies is probably not due to the special activity of solvents in the original magma along that contact. The explanation seems to lie partly in the different liability of the roof-rocks and floor-rocks to metamorphic change, but yet more in the metamorphic effects of water vapor set free in the digestion of the invaded hydrous sediments. This water vapor may have also assisted in the solvent work of the magma at the main upper contact, and, finally, in increasing the fluidity of that magma.

Magmatic Differentiation.—The development of basic, intermediate and acid zones in each of the sills is, thus, believed to have been the result of the density stratification of the compound magma of assimilation. The efficiency of differential density in separating out lighter acid material from the heavier basic, has been ably discussed and affirmed by Loewinson-Lessing.* It is unnecessary to recapitulate his argument, with which the present writer is in full accord.

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* Op. cit., pp. 344–354.

Loewinson-Lessing points out that when large amounts of foreign rock-material is digested in a magma, there is established a special tendency toward a systematic differentiation of the mixture.* Liquation will then take place when the cooling mixture reaches a certain temperature. The same author also holds that, according to the principles of physical chemistry, a magma becomes actually more fluid as a result of digesting foreign material. Differentiation is thereby facilitated. Vogt's valuable researches tend to corroborate this view.†

The granites and granophyres of the Moyie sill, of the Pigeon Point intrusive, and of the Sudbury sheet are to be regarded as not directly or merely due to the contact solution of sedimentary rocks and schists by gabbro; they are controlled in their final composition by a common process of differentiation supplementary to the gravitative effect. At Pigeon Point the acid rock, whatever its structure and grain, is a rather definite mixture of oxides. This is illustrated in the analyses of granular soda granite, the "quartz keratophyre", and the porphyry of Little Brick Island near Pigeon Point.‡ For lack of sufficient analyses the same statement cannot be made concerning the Moyie sill, but within limits it applies to the huge Sudbury sheet.§

The acid zone may have won some of its soda from the original magma; the gabbro may now hold some of the potash with the silica derived from the micaceous and feldspathic quartzites and other sediments. It is obvious, however, that all the details of the chemical processes engaged in this type of magmatic separation (chemical affinity in magma disturbed by gravitative diffusion currents) cannot be worked out from existing data on the magmatic behavior of silicates.

The intermediate rock at all three localities may be regarded as occupying zones of incomplete differentiation.

Special interest attaches to the occurrence of the nickel ores along the lower contact of the Sudbury sheet. Barlow, Coleman, Vogt and Walker agree that these sulphides are soluble in magmas. The solubility is in inverse proportion to the acidity of those magmas.‖ The fact suggests that the sulphides have been precipitated from the norite which has been acidified by assimilation. The concentration of the ore on the lower contact is again the result of differentiation through contrasts of density, the sulphides settling to the bottom of the sheet. Loewinson-Lessing has already suggested this gen-

* Op. cit., pp. 375 ff.

† Op. cit., Part 2.

‡ Bull. 228, U. S. Geol. Surv., p. 89.

§ See A. P. Coleman, 1904 report, p. 213.

‖ J. H. L. Vogt, op. cit., p. 229.

eral hypothesis to explain the segregation of sulphide-ores, without, however, connecting the concentration with gravitative influence. Coleman has announced the view that the ores have thus settled to the bottom of the sill, but has not connected the action with the digestion of acid rock in the norite.* The whole array of facts connected with the Sudbury intrusive is so accordant with the double theory of assimilation and differentiation through density stratification, as to single out this particular case as perhaps, of all those noted in the present paper, the most convincing and illuminating.

It is necessary that brief reference be made to an alternative view of all these related phenomena. One may conceive that the granite-granophyre, intermediate rock and gabbroid rock in each of the intrusive sheets may be explained by simple differentiation from an *original* magma through density stratification but without the aid of significant assimilation of the country-rocks. Lack of space forbids that this hypothesis be here discussed at length. The writer believes that the hypothesis is untenable or, at least, is much less adapted to explaining the facts than the hypothesis of assimilation accompanied and followed by differentiation. Most of the facts on which that belief is founded have been already implied or expressly noted.

Among the significant facts are the following:

1. There is a close similarity in composition between the granite-granophyre zone and rims of manifest digestion about xenoliths now surrounded by gabbro. This consanguinity is inexplicable on the theory of mere differentiation within the original magma.

2. The genetic relationship between the granite-granophyre zone and the invaded sediments is further shown by certain special features already described among the structures of the acid rock in the Moyie sill, and of the overlying, metamorphosed quartzite. For example, the development of remarkably poikilitic quartz in the granite-granophyre and in the recrystallized quartzite (the quartz of the latter being largely or wholly indigenous) may be mentioned. This repeated occurrence of a peculiar structure finds no simple explanation on the pure-differentiation theory.

3. In the period of high temperature preceding the viscous period when the visible xenoliths were frozen in the gabbro, thousands or millions of other xenoliths were completely or in part digested in the gabbro magma. The product of their digestion can be found, apparently, in no other place than in the existing acid zone of each intrusive sheet.

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* 1903 report, p. 277.

4. Mere differentiation of an original magma (through density stratification) cannot readily explain the slight but certain excess of silica along the lower contact of the Moyie sill. That degree of acidification is readily understood on the assimilation theory.

5. Along the British Columbia boundary a large number of contemporaneous gabbro sills of practically identical mineralogical and chemical composition have been found. In most of these no true granite-granophyre zone occurs. The composition of these gabbros is essentially equivalent to that of the gabbro in the central part of the Moyie sill; yet, on the pure-differentiation theory we should expect a distinct difference of composition between these other sills and the basic pole of differentiation in the Moyie sill. The assimilation-differentiation theory finds no difficulty in the essential equivalence of composition.

6. The assimilation-differentiation theory demands that a great absolute amount of thermal energy be credited to a sill in which secondary granite has been formed; that sill must always be thick. Other things being equal, granite formed by mere differentiation from an original magma should be found also in sills of less thickness, though here again the absolute thickness must be considerable. True granite with the relations described in this paper has never been found as a continuous zone in any intrusive sheet 500 feet or less in thickness. On the pure-differentiation theory it is difficult to understand why differentiation should afford true granite in a sheet of the strength observed at Pigeon Point, and should not afford a true granite zone in a sheet 400 or 500 feet thick. The assimilation-differentiation theory readily interprets the fact as due to the relatively enormous amount of heat required for the generation of the granite-granophyre zone, namely, an amount of heat characteristic only of thick intrusive sheets.

7. The pure-differentiation theory has to face another difficult question which does not arise if the assimilation-differentiation theory be accepted. Why was differentiation in the original magma postponed to the moment of intrusion? This difficulty is, of course, by no means conclusive against the pure-differentiation theory, but it means one more unavoidable theoretical burden weighting the pure-differentiation theory in a way which renders, by contrast, the assimilation-differentiation theory one of relative simplicity and, by so much, of greater strength.

General Application.—In the foregoing discussion the secondary origin of some granites has been deduced from the study of intrusive sills or sheets; but it is evidently by no means necessary that the igneous rock body should have the sill form. The wider and more important question is immediately at hand—does the assimilation-differentiation theory apply to truly abyssal contacts? Do the granites of stocks and batholiths sometimes originate in a manner similar or analogous to that just outlined for the sills?

The writer has briefly noted general reasons affording affirmative answers to these questions.*

Gabbro and granophyre are often characteristically associated at various localities in the British Islands as in other parts of the world.† The field relations are there not so simple as in the case of the Moyie sill, for example, but otherwise the recurrence of many common features among all these rock-associations suggests the possibility of extending the assimilation-differentiation theory to all the granophyres. Harker's excellent memoir on the gabbro and granophyre of the Carrock Fell District, England, shows remarkable parallels between his "laccolite" rocks and those of Minnesota and Ontario.‡

At Carrock Fell there is again a commonly occurring transition from the granophyre to true granite, and again the granophyre is a peripheral phase. Still larger bodies of gabbro, digesting acid sediments yet more energetically than in the intrusive sheets, and at still greater depth, would yield a thoroughly granular acid rock as the product of that absorption with the consequent differentiation. This does not imply, of course, that all granites are of this origin, but it is quite possible that most intrusive granites are either of this origin or have been more or less modified through assimilation.

The difficulty of discussing these questions is largely owing to the absence of accessible lower contacts in the average granite body. All the more valuable must be the information derived from intrusive sills. The comparative rarity of such rock-relations as are described in this paper does not at all indicate the exceptional nature of the petrogenic events signalized in the Moyie, Pigeon Point or Sudbury intrusives. It is manifest that extensive assimilation and differentiation can only take place in sills when the sills are thick, well buried, and originally of high temperature. All these conditions apply to each case cited in the present paper. The phenomena described are relatively rare largely because *thick* basic sills cutting acid sediments are comparatively rare.

On the other hand, there are good reasons for believing that a subcrustal gabbroid magma, actually or potentially fluid, is general all around the earth; and secondly, that the overlying solid rocks are, on the average, crystalline schists and sediments more acid than gabbro. Through local, though widespread and profound, assimilation of those acid terranes by the gabbro, accompanied and followed by differentiation, the batholithic granites may in large part have been derived.* True batholiths of gabbro are rare, perhaps because batholithic intrusion is always dependent on assimilation.

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* This Journal, vol. xv, 1903, p. 269, vol. xvi. 1903, p. 107.

† See A. Geikie, Ancient Volcanoes of Great Britain, 1897.

‡ Quart. Journal Geol. Soc., vol. l, 1894, p. 311 and vol. li, 1895, p. 125.

The argument necessarily extends still farther. It is not logical to restrict the assimilation-differentiation theory to the granites. The preparation of the magmas from which syenites and diorites, for example, have crystallized, may have been similarly affected by the local assimilation of special rock-formations. The development of some of the anorthosites of the Canadian and Adirondack Archean was possibly conditioned on the digestion of part of the associated crystalline limestones by plutonic magma.

The officers of the Minnesota Geological Survey have shown that the same magma represented in the soda granite and granophyre of Pigeon Point forms both dikes and amygdaloidal surface flows.† The assimilation-differentiation theory is evidently as applicable to lavas as to intrusive bodies. But demonstration of the truth or error of the theory will doubtless be found in the study of intrusive igneous bodies rather than in the study of volcanoes either ancient or modern.

Finally, the fact of "consanguinity" among the igneous rocks of a petrographical province may be due as much to assimilation as to differentiation.

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* Cf. R. A. Daly, op. cit.

† N. H. Winchell, Final Rep. Minn. Geol. Surv., vol. 4, 1899, pp. 519–22.

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THE OKANAGAN COMPOSITE BATHOLITH OF THE CASCADE MOUNTAIN SYSTEM

BY

REGINALD A. DALY

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THE OKANAGAN COMPOSITE BATHOLITH OF THE CASCADE MOUNTAIN SYSTEM*

BY REGINALD A. DALY

(Read before the Society December 30, 1905)

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INTRODUCTION

From end to end the Coastal division of the North American Cordillera, including the Sierra Nevada, Cascade Mountain system, the British Columbia Coast range, the Alaska, Saint Elias, and other ranges, comprising an area more than six times that of the Alps of Europe, is now proved to inclose granitic masses of great size and importance. Most of them are of post-Archean dates, and it is even probable that the greater number belong to post-Paleozoic epochs.* Many of the Californian stocks and batholiths and a few batholithic masses in the state of Washington have been carefully studied. Much work has been done, too, in the yet more extensive granitic fields of Alaska and British Columbia; but this work has generally been incidental to long reconnaissance surveys, wherein detailed investigations could not be profitably undertaken. In the Sierra Nevada the post-Paleozoic granitic rocks—granodiorites—are largely, if not entirely, of Mesozoic age. In Alaska and northern British Columbia the great "Coast Range batholith" is reported to be of very similar composition, but details as to the development of this colossal body are still largely lacking. Midway in this vast coastal mountain division lies the International boundary, at the 49th parallel of latitude.

On that line the writer has constructed a geological section which throws light on the nature and origin of the granites and tends to bring out the connection between the widely distant northern and southern regions, where Cordilleran study is now being so energetically pursued in government surveys. The results of the work on the 49th parallel corroborate some of the leading conclusions of Dawson, Russell, Willis, G. O. Smith, Calkins, Mendenhall, and others who have carried on researches in the adjacent parts of Washington and British Columbia. The solution of the problems of these granites, as of all granites, primarily demands the patient, careful accumulation of field facts. The big scale of the phenomena, their unusually perfect exposure among these splendid mountains, and the mere fact that much of the area described has never been touched with a geological hammer are other reasons for placing on record the results of the Boundary survey.

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*Cf. A. C. Lawson, Journal of Geology, Chicago, vol. 1, 1893, p. 579.

GEOGRAPHICAL SUBDIVISION OF THE CASCADE MOUNTAIN SYSTEM

In 1901 Messrs G. O. Smith and F. C. Calkins, of the United States Geological Survey, made a reconnaissance survey of the 10-minute strip crossing the Cascade range immediately south of the 49th parallel. Their report gives a succinct account of this part of the mountain system which may well serve to locate the region here to be treated. Two paragraphs may be quoted from the report:

> In northern Washington, where the Cascade mountains are so prominently developed, the range is apparently a complex one and should be subdivided. This was recognized by Gibbs, who described the range as forking and the main portion or "true Cascades" crossing the Skagit where that river turns west, while the "eastern Cascades" lie to the east. Bauerman, geologist to the British commission, recognized three divisions, and as his subdivision is evidently based upon the general features of the relief it will be adopted here. To the eastern portion of the Cascades, extending from mount Chopaka to the valley of Pasayten river, the name of Okanagan mountains is given, following Bauerman. To the middle portion, including the main divide between the Pasayten, which belongs to the Columbia drainage, and the Skagit, which flows into Puget sound, Bauerman gave the name Hozomeen range, taken from the high peak near the boundary. For the western division the name Skagit mountains is proposed, from the river which drains a large portion of this mountain mass, and also cuts across its southern continuation. It will be noted that the north-south valleys of the Pasayten and the Skagit form the division lines between these three subranges, which farther south coalesce somewhat so as to make subdivision less necessary.
>
> The Okanagan mountains form the divide between the streams flowing north into the Similkameen and thence into the Okanagan and those flowing south into the Methow drainage. In detail this divide is exceedingly irregular, but the range has a general northeast-southwest trend, joining the main divide of the Cascades in the vicinity of Barron. The highest peaks, such as Chopaka, Cathedral, Remmel, and Bighorn, have a nearly uniform elevation of 8,000 to 8,500 feet and commonly are extremely rugged. Over the larger portion of this area the heights are above 7,000 feet, and below this are the deeply cut valleys.*

The sketch map, figure 1, shows the position of the boundary line in the Cordillera and of the section described in the present paper.

AREA COVERED BY THE BOUNDARY COMMISSION SURVEY

Since the year 1901 the United States surveyors attached to the International Boundary Commission have prepared an excellent contour map

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*Bulletin no. 235, U. S. Geological Survey, 1904, p. 14.

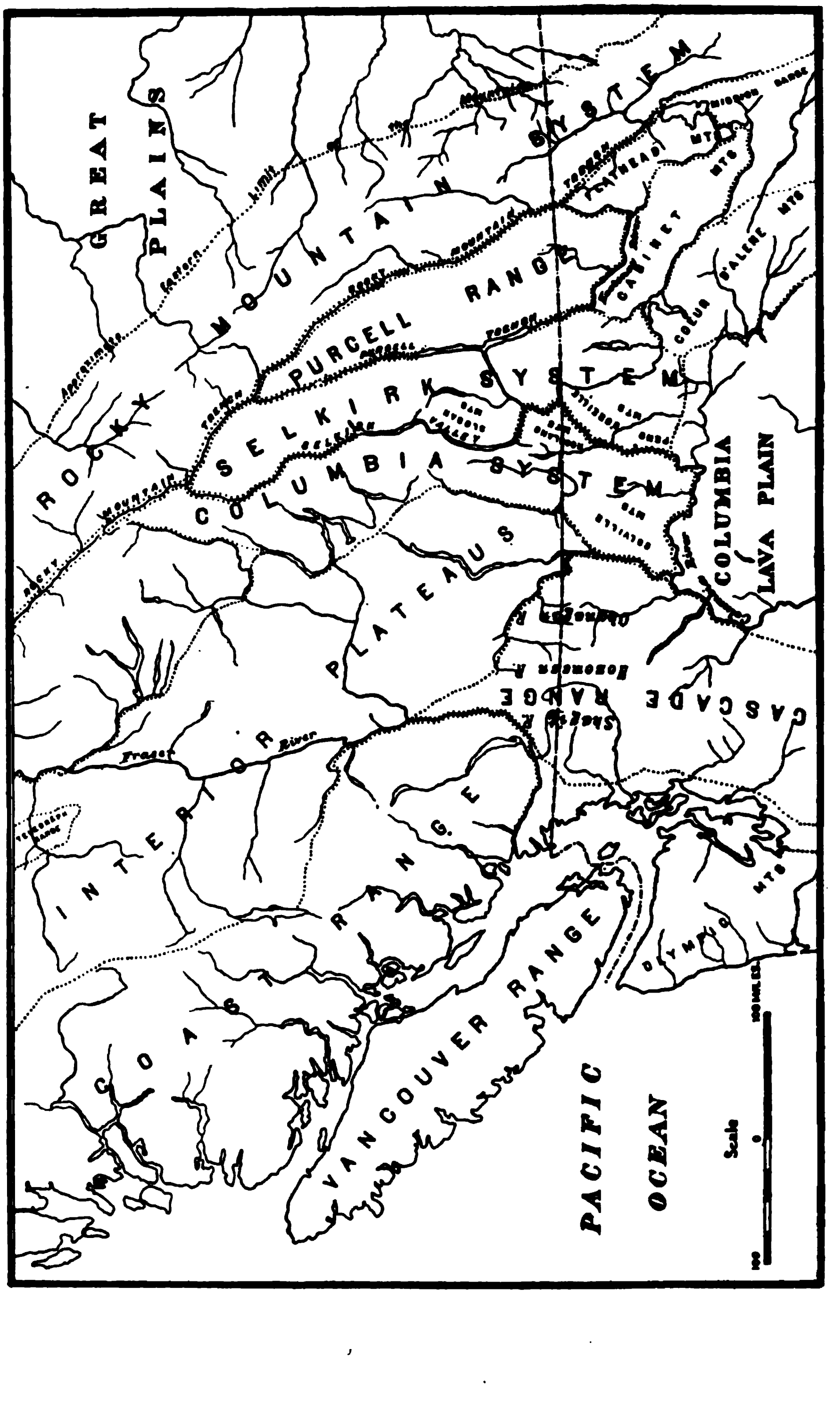

FIGURE 1.—*Map showing Relation of Cascade Range to other Members of the Cordillera.*

of a belt crossing the Cascades between the Similkameen and Skagit rivers and exactly bisected by the international line. To the officials at Washington the writer is indebted for the use of this map in manuscript. The belt averages 5 miles in width. The geology of the belt has been plotted on the map, and the section has been continued eastward by the use of a contour map of a similar 5-mile belt crossing the Interior plateaus east of Similkameen river; in the latter map the international line forms the southern limit. The total area of the belt which is of present interest is about 400 square miles. The part lying within the Hozomeen range—that is, west of Pasayten river—covers greatly deformed strata of Cretaceous age. The remainder, or three-fourths, of the belt is underlaid by the vast assemblage of plutonic intrusive rocks which had been briefly described by Smith and Calkins.

This strip of rugged mountains forms part of a huge batholithic area that will be adequately mapped only after many more seasons of arduous field-work. The geological findings within such a belt as now to be described would be much increased in value if they could be systematically compared with field studies throughout the whole batholithic province. For many reasons such a complete survey is now impracticable. The present paper is thus a sort of report of progress on the geology of these crystalline rocks of the northern Cascades. Nevertheless discoveries of prime importance to the geology of the entire range have been made within even the limited area of the 5-mile belt. Certain of the broader conclusions there deduced may, it is believed, be relied on, and will not need serious emendation as the exploration of the mountains continues. In the following pages there is offered another class of considerations which are theoretical and need the facts of the field, especially of the whole Cascade field, for their full discussion. In these matters particularly, a 5-mile belt can not speak for the whole Okanagan range, except as geological experience in that belt accords with verified geological experience the world over.

GENERAL DESCRIPTION OF THE BATHOLITHIC AREA AND LOCATION AND RELATIVE SIZE OF ITS UNITS

From the eastern slope of the wide valley occupied by Osoyoos lake to the Pasayten river, an air-line distance of just 60 miles along the boundary, the mountains are composed of almost continuous plutonic igneous rocks. This immense mass is markedly heterogeneous. To simplify the following discussion it will be well to review the general geographical relations among the different geological units. To the same end it is convenient to adopt a special name for each unit. The diagrammatic cross-section, figure 2, shows the units in their relative positions.

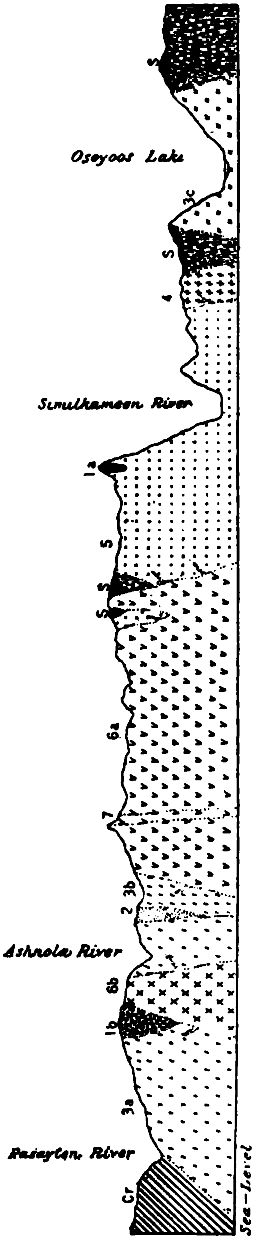

FIGURE 2.—*Diagrammatic east-west Section through the Okanagan Composite Batholith.*

S —Schists and associated Paleozoic rocks.
Cr—Pasayten Lower Cretaceous arkose sandstones.
1a—Chopaka peridotite.
1b—Basic complex.
2 —Ashnola gabbro.
3a—Remmel batholith, Western phase.
3b—Remmel batholith, Eastern phase.
3c—Osoyoos batholith.
4 —Kruger alkaline body.
5 —Similkameen batholith.
6a—Cathedral batholith, Older phase.
6b—Park granite stock.
7 —Cathedral batholith, Younger phase.

The components of the batholith are numbered in order of intrusion. Horizontal scale, one inch to ten miles; vertical scale, one inch to two miles. The vertical exaggeration makes contact lines generally too steep. On a natural scale the basic bodies, 1a, 1b, and 2, would be shown as extending deeper into the granites; the actual distortion is intended to illustrate the "pendant" nature of each body.

The most easterly component body occupies both slopes of Osoyoos Lake valley; it is the southern part of a great batholithic mass of granodiorite and may be called the Osoyoos batholith. The most westerly unit extends from Pasayten river to within a mile or so of Cathedral peak. It is also a batholith of granodiorite and seems to compose the cliffs of the conspicuous mount Remmel 5 miles south of the boundary. This mass may be called the Remmel batholith. Immediately to the eastward of the Remmel a third large batholith, this time composed of a quite different rock, true biotite granite, underlies all of the belt as far as Horseshoe mountain, on the divide between the Ashnola and main Similkameen rivers. This may be called the Cathedral batholith—named after the fine monolithic mountain occurring within the limits of the granite. The fourth principal unit lies between the Cathedral and Osoyoos batholiths; it is composed of a batholithic soda-rich hornblende-biotite granite which is trenched by the deep valley of the Similkameen river, and an appropriate name for it is Similkameen batholith. These four principal units make up five-sixths of the whole area here described.

The subordinate geological members (excluding dikes) within the batholithic area are eight in number.

The largest of these consists of apparently Paleozoic schists, quartzites, greenstones, and other rocks forming the ends of two tongues that enter the belt respectively from north and south (see figure 3). These rocks occur on the roughly tabular "Kruger mountain," and for present purposes may be called the Kruger schists. The two schist tongues adjoin the Osoyoos batholith and nearly cut it off completely from direct contact with other plutonic units in the belt.

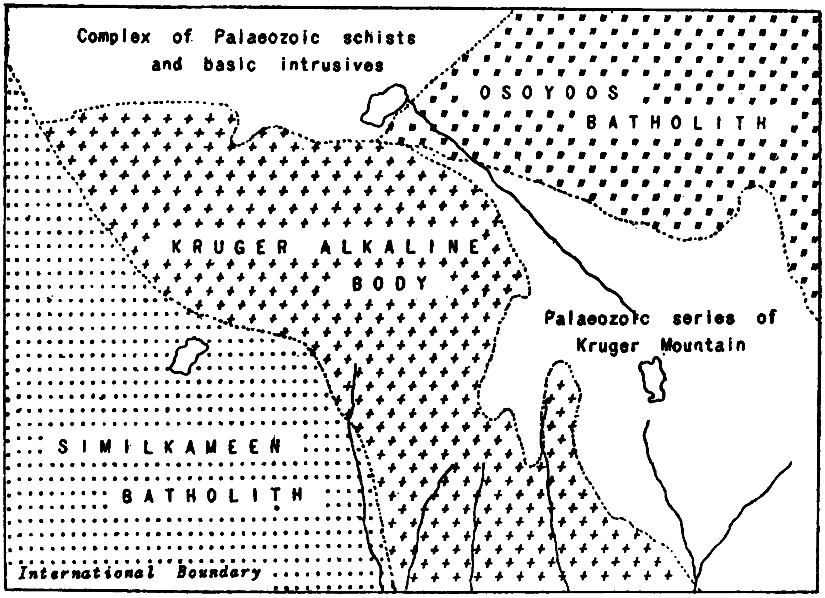
Complex of Palaeozoic schists and basic intrusives
OSOYOOS BATHOLITH
KRUGER ALKALINE BODY
Palaeozoic series of Kruger Mountain
SIMILKAMEEN BATHOLITH
International Boundary

FIGURE 3.—*Ground Plan showing Relations of the Osoyoos, Similkameen, and Kruger igneous Bodies and the invaded Paleozoic Formations.*

Scale, 1 : 110,000.

Between the Kruger schists and the Similkameen batholith is a comparatively small area of highly composite intrusives belonging to the malignite and nepheline-syenite families (see figure 3). These crop out on the western summits of the Kruger Mountain plateau and may be referred to as the Kruger Alkaline body.

The Similkameen granite preserves what seem to be remnants of its once complete roof (see figure 4). Chopaka mountain is crowned with a large patch of schist very similar to the Kruger schist. This Chopaka schist is cut by a strong body of gabbro apparently transitional into pure olivine rock—the Chopaka Basic intrusives. The whole forms a huge irregular block of roof rock almost completely surrounded and probably underlain by the Similkameen granite. Such a block, once a downwardly projecting part of a roof in stock or batholith, may be named a "roof pendant;" it is analogous to the pendant of Gothic architecture.

A brief digression on this conception may be permitted. Unusually fine examples of roof pendants are illustrated in the great slabs of bedded rocks interrupting the areas occupied by the batholiths of the Sierra Nevada. One of the most recent descriptions is published by Messrs Knopf and Thelen, following the lead of Lawson in a study of Mineral King, California.* Other examples, so well treated by Barrois, were found during the detailed geological survey of Brittany.† In all these and many other cases, and yet more clearly than on the 49th parallel, the masses of country rock (invaded formation) form respectively parts of a once continuous roof. The often perfect preservation of the regional strike in each of many examples very strongly suggests that these slabs have not sunk independently in their respective magmas. Such partial foundering would have almost inevitably caused some twisting of the block out of its original orientation. Granite and block have come into present relations because the magma, and not the block, was active. The point is of importance, as it bears on the mechanics of intrusion in these instances. It is further worthy of note that determination of roof pendants and their distribution may sometimes lead to the discovery of the approximate constructional form of batholiths.

A small pendant, composed of amphibolitic and micaceous schists and of quartzite, occurs on the north slope of Horseshoe mountain; another of similar constitution flanks the summit of Snowy mountain.

In all three cases the pendants appear in the highest portions of the batholith as now exposed in the belt; yet each block projects downward, deep into the heart of the granite mass.

A long slab of gabbro, ranging with the Cathedral fork of Ashnola river, is similarly a roof pendant to the Remmel batholith; it may be called the Ashnola gabbro (see figure 5). A still larger pendant, composed of gabbros and peridotites, lies in the Remmel batholith just west of the main valley of the Ashnola. On account of the extraordinary diversity of rocks and of rock structures in this pendant, it may be called the "Basic complex" (see figure 6).

Northeast of the complex is an elliptical stock of biotite granite, intrusive into both the Remmel granodiorite and the Basic complex. The

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*Bulletin of the Department of Geology, University of California, vol. iii, no. 15, 1904, and vol. iv, no. 12, 1905.

†C. Barrois: Annales, Société Géologique du Nord, many volumes, especially vol. 22, 1894, p. 181.

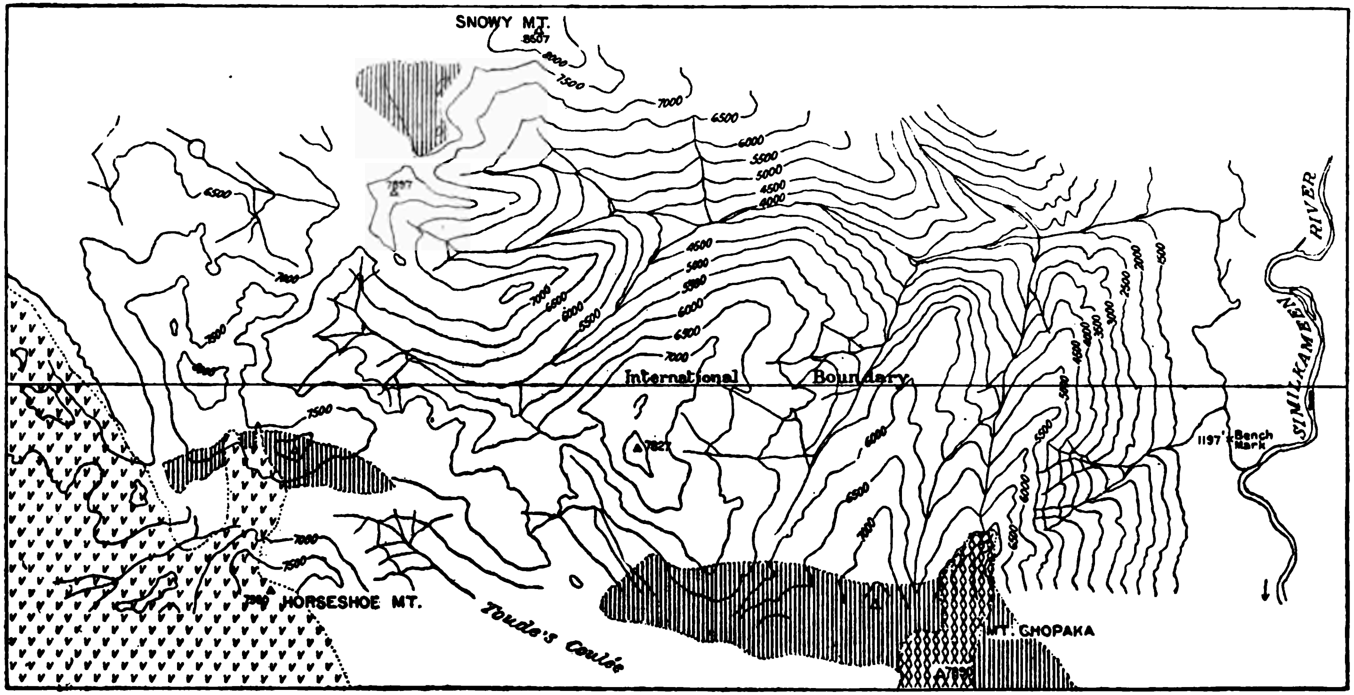

FIGURE 4.—*Map of the Similkameen Batholith, the Cathedral Granite Batholith, and the Chopaka basic intrusive Body.*

The Similkameen batholith (left blank) bears three roof pendants of schist (verticallining) and is cut by the Cathedral granite batholith (inverted carets). The Chopakabasic intrusive body (gabbro and dunite), cutting schists, but older than the Similkameen granite, is shown with crosses. Contour interval, 500 feet; scale, 1 ; 120,000.

white, massive outcrops of the granite are very conspicuous on the northern spurs of Park mountain; the rock may be referred to as the Park granite (see figure 6).

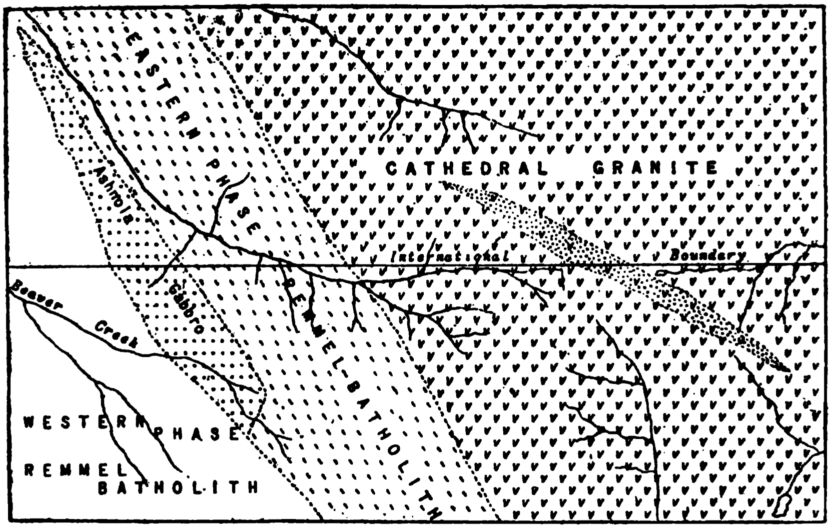

FIGURE 5.—*Ground Plan showing Relations of the Cathedral and Remmel Batholiths and the Ashnola Gabbro.*

The Younger phase of the Cathedral batholith is shown by stippling. The remarkably straight contact line of the Cathedral granite lies sensibly parallel to the gneissic banding in the Remmel batholith, Eastern phase. Scale, 1 : 120,000.

Within the 5-mile belt these various rock bodies occupy areas shown in the following table. The bodies are noted in order from east to west, beginning on the east:

	Square miles
Osoyoos batholith	50
Kruger schist	15
Kruger Alkaline body	9
Similkameen batholith	75
Chopaka schist	2
Chopaka basic intrusives	1¼
Horseshoe schist (pendant)	1
Snowy schist (pendant)	¾
Cathedral batholith	61
Remmel batholith	64
Ashnola gabbro (pendant)	1½
Basic complex (pendant)	6½
Park Granite stock	9
Total	296

The batholiths and the Kruger schist extend far to the north and to the south of the belt, so that the total area of each is much greater than is shown in the table. The figures given for all the other bodies represent nearly their respective total areas. Less than 7 per cent of the belt is underlaid by rocks not clearly plutonic in origin, and of that 7 per cent perhaps half is greenstone or other igneous rock. The 3 or 4 per cent of non-igneous rock is chiefly concentrated in the tongues of Kruger schist.

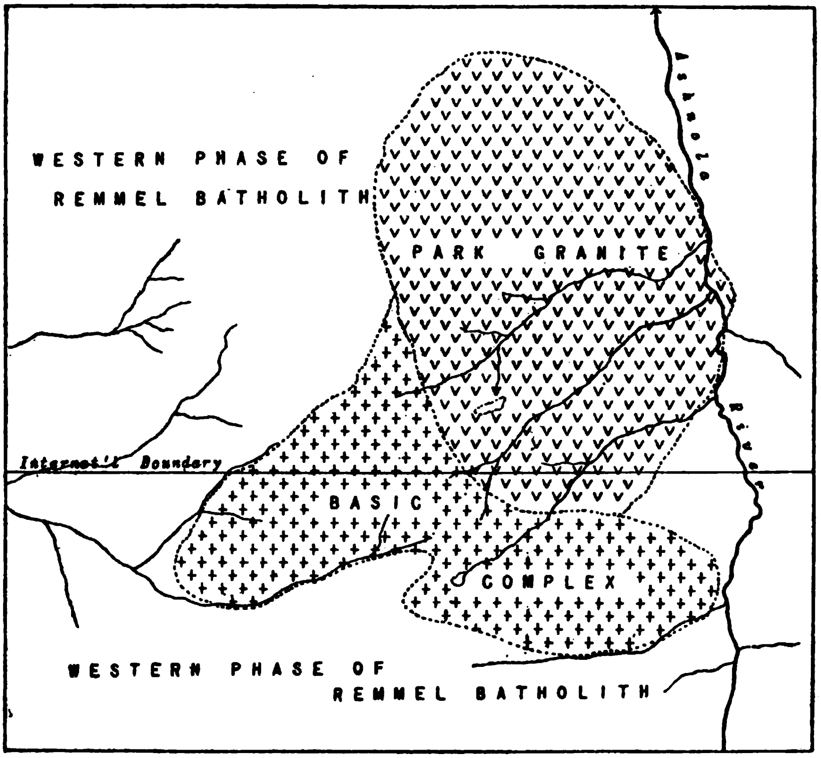
WESTERN PHASE OF REMMEL BATHOLITH
PARK GRANITE
Ashnola
River
International Boundary
BASIC COMPLEX
WESTERN PHASE OF REMMEL BATHOLITH

FIGURE 6.—*Ground Plan showing Relations of the Remmel Batholith, Park Granite, and Basic Complex.*

Scale, 1 : 120,000.

The tongues have been completely cut asunder by the plutonics; it is now possible to walk from one end of the belt to the other, the whole distance of 60 miles, and not once set foot on bed-rock which is other than of deep seated, igneous origin (see figures 2 and 3).

UNITY OF THE COMPOSITE BATHOLITH

Barring a few shreds and patches, the enormously thick pre-Paleozoic, Paleozoic, Mesozoic, and Tertiary sediments and schists represented in the Cordillera elsewhere are wanting in this part of the Cascade system. With thicknesses running into tens of thousands of feet, they once unquestionably composed the Okanagan range, and of them the ancestors of these very boundary mountains were built. Erosion has removed some of the formations, attacking the earth's sedimentary crust from above. There is every reason to believe that perhaps even more of the old mountain substance was removed during the successive batholithic intrusions. Thus the sedimentary crust has also been attacked from beneath; its integrity has been destroyed through the displacing or replacing of sediments by igneous magma. In bringing about this gigantic result all the batholiths have acted together. Though they are of very different ages, their energies have been devoted to a common work. Their effects are so integrated that in causing the nearly complete disappearance of the ancient strata they have imitated on a larger scale what occurs with any homogeneous batholith. From this point of view the Boundary belt, stretching from the eastern contact of the Osoyoos batholith to the western contact of the Remmel batholith, forms a small segment of one composite batholith somewhat broader than the Okanagan range. To emphasize this primary fact, the title of the present paper has been chosen.

Petrography of the Composite Batholith

IN GENERAL

Before proceeding to a detailed statement of the structure and history of the composite batholith a brief petrographical description of its components will be necessary. The chemical study of these rocks has only begun, but, on account of their freshness and coarseness of grain, microscopic analysis has been found so trustworthy that the different types can be already sufficiently well classified for the purposes of this discussion of the general geology. Much of the usual petrographical detail has been omitted as not bearing directly on the main problems.

The rocks will be described as nearly as possible in the order of their respective dates of intrusion.

CHOPAKA BASIC INTRUSIVES

The basic and ultra basic intrusives of the Chopaka roof pendant have been described by Smith and Calkins as uralitic gabbro, serpentines, and pyroxenites. Within the area covered by the Commission map (figure 4), the present writer has found no pyroxenite, but has referred all the massive intrusives of the Chopaka pendant (excluding dikes) to two rock types and their metamorphic derivatives.

Most of the rock within the area is feldspathic and seems to belong to a fairly steady type—normal gabbro transitional to metagabbro. It is a dark gray-green, medium grained, hypidiomorphic granular rock, originally composed of essential labradorite (Ab_1An_1) and diallage and accessory apatite, with a little magnetite. Crush metamorphism, supplemented by ordinary weathering, has largely changed the diallage into actinolitic amphibole, both compact and smaragditic. The specific gravity of the least altered rock is 2.959, taken, as were all the other specific gravities to be mentioned, at room temperatures.

That common rock type is associated with a large body of a dark greenish gray, fine grained rock of which several specimens show the composition very clearly. It was originally made up entirely of granular olivine without any certain accessory constituent. No trace of chromite has been found. Serpentine, talc, tremolite, and magnetite are present in most of the thin-sections, but apparently in all cases as decomposition products of the olivine. The specific gravity of the rock varies from 3.100 to 3.173. It is a dunite without chromite.

The field relation of the gabbro and olivine rock has not been determined. They may belong to distinct intrusions or they may be due to differentiation within a single body. Though transitions seemed to appear in the actual outcrops, the search for final evidence in these rocks, crushed and obscured as they are, has so far proved unavailing. Analogous occurrences in other parts of the boundary belt suggest that gabbro and olivine rock were intruded at different dates.

ASHNOLA GABBRO

Throughout its 5 miles of length the Ashnola gabbro body is homogeneous in composition, but often varies abruptly in grain from medium to quite coarse. The color is uniformly a peculiar deep fawn, which is the dominating tint of the feldspar. This color is rather remarkable, as the rock proves under the microscope to be quite fresh, with feldspars of glassy clearness. The essential constituents are a green augite, often colorless in thin-section, brownish green hornblende, brown biotite, and labradorite, Ab_5An_6. Abundant apatite, some magnetite, and a very little interstitial quartz are the accessories. The structure in the original rock is the hypidiomorphic granular, though the augite is often, especially in the coarser grained phases, poikilitic. Regular intergrowths of the augite and hornblende are common. The rock is an augite-hornblende-biotite gabbro, the specific gravity of which averages 2.946.

Although the gabbro is older than the Remmel granodiorite and has shared in the great dynamic metamorphism which, as we shall see, has profoundly affected the more acid rock, there is far less crushing action manifest in the gabbro than in the granodiorite. Gneissic structures were indeed sometimes seen in the ledges, but banding was never discovered and the granulation is seldom comparable to that of the Remmel. It is, moreover, suspected that some of the gneissic arrangement of minerals in the gabbro is due to fluidal alignment of its tabular feldspars in the original magmatic period. For some unknown reason the gabbro has resisted crushing and shearing better than the granodiorite.

BASIC COMPLEX

Petrographically and structurally, the Basic complex is perhaps the most steadily variable plutonic masses in the entire boundary section from the Great plains to the Pacific. It covers an area stretching from Ashnola river westward over Park Mountain ridge, a distance of 5 miles. The extreme north-and-south diameter is about 3 miles, and the total area is nearly 7 square miles. The Remmel granodiorite once completely surrounded the complex, which, as above noted, is in pendant relation to the batholith. The pre-Remmel extent of the complex was greater than the area now exposed; how much of it was destroyed during the Remmel intrusion it is impossible to say. The part thus remnant was still further diminished during the intrusion of the Park granite, which now, as illustrated on full 3 miles of contact line, projects strongly into the body of the complex. A large block of the latter formation, measuring about 400 yards in length by 200 yards in width, was found within the Park granite mass itself; it may represent a roof pendant in the stock, and thus a small analogue to the larger basic body in its relation to the Remmel batholith.

The Basic complex is made up of a remarkable assemblage of basic plutonic rocks of at least three different periods of intrusion. The oldest types are coarse grained. They include highly irregular bodies of hornblendite, which in the field is often seen to be transitional into a labradorite-bearing hornblende-augite peridotite; this in its turn merges into hornblende-augite gabbro. All of these rocks are believed to be of contemporary origin. Their occurrence is so sporadic that it is difficult to say how much of the whole basic area they really cover—possibly one-quarter of it by rough estimate. These rocks are cut by many large dikes and more irregular masses of hornblende-gabbro, augite-hornblende gabbro, and hornblende-biotite quartz gabbro. Such types are of medium to coarse grain. Their specific gravity varies from 2.873 to 2.986.

One 40-foot dike cutting the younger gabbros singles itself out as a unique petrographic type. It is an amphibole peridotite in which the olivine occurs in large, potato-shaped or ellipsoidal, coarse grained nodules from 1½ to 2 inches in diameter. These nodules are thickly and quite uniformly scattered through a coarse matrix of green hornblende. The dike is interesting on account of its peculiar structure, but is of little importance as a member of the complex as a whole; no other dike of the kind was found.

As there is no discoverable system in the differentiation of the earliest intrusive members, varying as they do most capriciously from ledge to ledge, so there is no discoverable system in the trends or occurrence of the countless later injections of the gabbros. The complication has been still further increased by the intrusion of thousands of narrow and broader dikes of granite. Much of the granite is apophysal or aplitic from the Remmel batholith; some of it is apophysal from the magma supplying the Park granite stock, while many dikes of acid pegmatite locally traverse the whole mass. The complication was finally made perfect through the enormous crushing which the Basic complex underwent, both during the intrusion of the granites and during the orogenic revolution when the Remmel granodiorite itself was sheared into banded gneisses.

In the shearing of the Basic complex its material was metamorphosed and, in part, it migrated. The mode of migration is believed to be that which will be briefly discussed in connection with the petrographic descriptions of the crushed Osoyoos and Remmel batholiths. The metamorphism has developed many schistose phases, among which hornblende-biotite-diorite gneiss (specific gravity, 2.766 to 2.863) and well foliated hornblendite are common.

As a result of this long and varied history, scarcely any two ledges within the area of the Complex accord in composition. The constitution of what appears to be the commonest phase of the Complex, the augite-hornblende gabbro, and the peculiar fawn color of its feldspar furnish a probable correlation of part of the whole mass with the Ashnola gabbro. There is no certainty of similar correlation with the basic rocks of mount Chopaka.

OSOYOOS GRANODIORITE BATHOLITH

Macroscopic and microscopic characteristics.—The original rock of the Osoyoos batholith is a typical medium to coarse grained granodiorite. The color is the familiar light gray characteristic of monzonites, granodiorites, and some other granular rocks rich in plagioclase. In the likewise fresh though somewhat metamorphosed phases the rock assumes a light greenish gray tint due to the dissemination of metamorphic biotite or to the abundant development of epidote. All phases weather light brownish gray. The essential constitutents are deep green hornblende, brownish green biotite, orthoclase, quartz, and unzoned andesine, Ab_5An_3. The accessory minerals are apatite, magnetite, and titanite; none of these may be called abundant. Allanite in rather large amount is accessory in the basified contact zone. Colorless epidote is invariably present, but is regarded as of metamorphic origin. Where it becomes abundant the iron ore has partially or wholly disappeared; then probably entering into the composition of the epidote. Biotite is generally dominant over hornblende and plagioclase over orthoclase.

Along the eastern contact of the batholith the average plagioclase is labradorite, Ab_1An_1, and it so far replaces the orthoclase that the rock here verges on quartz diorite. In the hand specimen this somewhat basified contact phase is indistinguishable from the true granodiorite. The limits of the orthoclase-poor zone were therefore not closely fixed in the field. It is probable that the zone is not more than a few hundred yards in width, and that the original rock of the batholith was, in the large, homogeneous. A second exceptional phasal variation is founded on the disappearance of hornblende in rock that shows decided cataclastic structure, other constituents remaining the same as in the normal granodiorite. This phase—gneissic biotite granite rich in andesine—occurs sporadically in the heart of the batholith. Very possibly it is not of original composition, the hornblende having been removed through metamorphic action.

Dynamic and hydrothermal metamorphism of the granodiorite.—In the mapped area of the batholith scarcely a single outcrop can be found that does not show the powerful effects of intense orogenic strains. Even the most massive phases show, under the microscope, the varied phenomena of crushing stress—granulation, bending of crystals, undulatory extinctions, recrystallization, etcetera. Because of the crushing, the average rock is no longer the original rock. The granodiorite has been changed into several metamorphic types, of which three may be noted.

The commonest transformation is that into a biotite-epidote-hornblende gneiss, with essential and accessory constituents like those in the original granodiorite, but in somewhat different proportions. The color is light gray, with a green cast on surfaces transverse to the schistosity; parallel to the schistosity a dominant and darker green color is given by abundant fine-textured leaf aggregates of biotite. These aggregates are not simply crushed and rotated original mica foils, but, like the epidote, represent true recrystallization and the incipient migration of material within the granulated, plutonic rock. At the same time much of the original hornblende, apatite, and magnetite have been removed.

A second metamorphic type is a yet more highly schistose biotite-epidote gneiss often transitional into biotite schist. The essential constituents are biotite, epidote, orthoclase, andesine, and quartz. The accessories include very rarely apatite and magnetite, while titanite seems to have entirely disappeared along with the hornblende. Orthoclase seems here to be more abundant than plagioclase. The quartz and feldspars are intensely granulated and, with polarized light, are full of strain shadows. The rock is more richly charged with biotite than the hornblende-bearing gneiss.

The third metamorphic type occurs in immediate association with the gneiss just described, being interbanded with it. It is a fine grained, strongly schistose, dark greenish gray hornblende gneiss of basic character. The essential minerals are idiomorphic green hornblende and allotriomorphic feldspars in mosaic with considerable interstitial quartz; the last is hardly more than accessory. The feldspar is mostly unstriated and not easy of determination. Orthoclase seems to be dominant, but, as shown by extinctions on (010), approaches soda-orthoclase in composition. The plagioclase is possibly andesine. Titanite, apatite, and well crystallized magnetite are accessory in large amounts. The hornblende prisms are often twinned parallel to (010). That crystallographic plane now lies characteristically parallel to the plane of schistosity. Except for the soda content of the orthoclase, the minerals all appear to have the same characters as in the granodiorite.

This third phase occurs in zones of maximum shearing in the batholithic mass. It is believed to represent a new secondary rock formed by the recrystallization of the materials leached out of the other two metamorphic phases just noted and out of the granodiorite as it was crushed. The recrystallization either accompanied or followed the very closing stage of the orogenic crushing. This fact is demonstrated by the entire absence of granulation or even undulatory extinctions in the mineral components.

The probable history of the metamorphism may now be summarized. After the complete solidification of the original granodiorite, very intense crushing stresses affected the whole body. The straining and granulation of the minerals exposed them to wholesale solution, whether in water and other fluids mechanically inclosed in the rock or in fluids of exotic origin. This process of solution was hastened by the rise of temperature incident to violent crushing. All the minerals must have been affected, but it appears that the hornblende, biotite, magnetite, apatite, and titanite were most likely to be dissolved and so migrate with the fluids that slowly worked their way through the rock in its mechanical readjustments.* Escape for the mineral-laden fluids was most ready in the zones of maximum shear. Thither the fluids were drawn, and there some of the dissolved material recrystallized so as to develop the darker colored bands of biotite-epidote gneiss, biotite schist, and hornblende gneiss.

Where the granulation was least the granodiorite retains nearly its original composition, though epidote may be formed; the specific gravity averages 2.746. Where the granulation was more pronounced, as in the first metamorphic type described, much of the hornblende, titanite, magnetite, and apatite have been leached out and abundant metamorphic biotite and epidote have formed; the result is a biotite-hornblende-epidote gneiss with a density less than that of the original granodiorite because of the loss in heavy constituents (specific gravity, 2.692). A further stage of granulation and energetic shearing led to the formation of perfect schistosity in rock made up of the quartz-feldspar ruins of the original rock, cemented by very abundant biotite and epidote—the biotite-epidote gneiss (specific gravity, 2.783). The fissures and fluid-filled cavities developed in the zones of maximum shear are now occupied by the strongly schistose hornblende gneiss (specific gravity, 2.939) and similar products of complete solution, migration, and subsequent complete recrystallization.

The granodiorite has thus become not only mechanically crushed, but to a large extent rendered heterogeneous. It is now not only gneissic, but banded in zones of new rock markedly varied in composition. The schistosity and banding everywhere agree in attitude; the strike varies from north 10 degrees west to north 75 degrees west, but over large areas, as indeed over the whole batholith east and west of Osoyoos lake, averages north 45 degrees west almost exactly. Neglecting minor crumplings, the dip varied from 70 degrees northeast to 90 degrees, averaging about 82 degrees northeast. This average attitude is close to that observed in the schists cut by the granodiorite, but represents an exceptional strike among the main structural axes of the Cordillera. It may be noted that shearing is much more manifest on the east side of Osoyoos lake than on the west side.

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*This conclusion has in this instance been deduced from the study of thin-sections. In general it accords with the results of experiment. Müller has found that in carbonated water hornblende and apatite are much more soluble than either orthoclase or oligoclase. Magnetite is less soluble than any of those minerals, but the relatively minute size of its crystals in granodiorite would allow of its complete solution and migration before the essential minerals had lost more than a fraction of their substance. It is also possible that magnetite would suffer especially rapid corrosive attack from fluid in which the chlorine-bearing apatite has gone into solution. Cf. R. Müller in Tschermak's Miner. und Petrog. Mittheilungen, 1877, p. 25.

REMMEL GRANODIORITE BATHOLITH

Physical and mineralogic characteristics.—There are many principal points of resemblance in composition between the extreme eastern and extreme western members of the composite batholith (see figure 2). The staple rock of the Remmel batholith is also a granodiorite. It is in color a light gray, weathering whitish to a light brownish gray; in grain, medium to rather coarse; in structure, eugranitic, though often somewhat porphyritic in look, through the development of large, black, lustrous biotites. These phenocrysts are sometimes perfectly idiomorphic, and then weather out in hexagonal plates about one centimeter in diameter. This commonest phase of the batholith is essentially composed of brownish green hornblende, biotite, quartz, orthoclase, and andesine which averages Ab_5An_3. Titanite is a fairly abundant accessory and is accompanied by apatite and by magnetite, often titaniferous. The specific gravity of this rock varies from 2.721 to 2.775, averaging 2.748.

Metamorphism.—Here again it is difficult to distinguish in the field any systematic variation of the original rock composition. If such variation ever were important, its discovery is rendered most uncertain through the profound metamorphic changes that have affected the batholith. Here, too, there has been tremendous shearing and crushing. A secondary gneissic structure has been formed over most of the batholith as exposed in the boundary belt. The shearing has been extraordinarily powerful in a north-south zone of the batholith running along the contact with the younger Cathedral batholith (see figure 5). In that zone, which extends westward as far as the Ashnola gabbro, the Remmel rock has been thoroughly changed from its original condition.

This "Eastern phase" of the Remmel is now remarkably banded. The broader bands are more or less massive biotite gneiss rich in oligoclase (Ab_6An_1), or orthoclase-bearing biotite quartz diorite gneiss. The color of these rocks is light gray, weathering white or light brown. Hornblende and titanite completely fail; apatite is accessory, but in small amount. A few reddish garnets are occasionally developed. There is seldom any indication of straining or crushing of the minerals constituting these bands. Microscopic study leaves the impression that the material of the bands has been wholly recrystallized. The specific gravity averages 2.651, and is thus considerably lower than in the normal granodiorite.

Alternating with the broad bands are very numerous dark green-gray, highly foliated zones of mica-gneiss and mica-schist, both very rich in biotite, but bearing no hornblende. These zones were regarded in the field as located along planes of maximum shearing. They accord very faithfully in attitude with a strike of north 2 to 25 degrees west and a dip nearly vertical, but sometimes 75 degrees or more to the east-northeast—structural elements induced by regional orogenic movements in the Cordillera. It is improbable that the banding represents peripheral schistosity about the Cathedral batholith. The chief reason for excluding this view is that peripheral schistosity is lacking in the great Similkameen batholith, which is also cut by the Cathedral granite. It appears, on the other hand, that the Remmel batholith was already crushed and its banding produced before either the Similkameen or Cathedral granite was intruded.

Six-sevenths of the total area mapped in the Remmel batholith is underlaid by hornblende-bearing rock much more nearly identical with the original granodiorite. In fact the description of the granodiorite has been based on specimens taken from the more massive rock facies occurring in the larger area. The rocks of this "Western phase" are crushed and sheared, but distinctly less so affected than the mass forming the Eastern phase. Where strong shear zones occur in the Western phase they are occupied by dark greenish-gray, fine grained, fissile hornblende gneiss very rich in hornblende and similar to the secondary filling of shear zones in the Osoyoos granodiorite. Between these narrow shear zones the more normal rock usually shows mechanical granulation and fracture rather than extensive recrystallization.

Interpretations of the Eastern and Western phase.—Three interpretations of the two phases are conceivable. They may be supposed to be distinct intrusions of two different magmas; or, secondly, original local differentiation products in the one batholith; or, thirdly, distinguished in their present compositions because of the unequal dynamic metamorphism of a once homogeneous magma. Against the first view is the fact that the two phases, where in contact, seem everywhere to pass insensibly into each other. In favor of the third view are several facts which do not square with the second hypothesis, and the writer has tentatively come to the conclusion that the third hypothesis is the correct one. Among those facts are the following:

1. The Eastern phase covers that part of the Remmel body which has suffered the greatest amount of dynamic stresses exhibited either in the Remmel or in any other of the larger components of the Okanagan Composite batholith. It has been seen that the less intense though still notable dynamic metamorphism of the Osoyoos granodiorite led to the special excretion of most or all of the hornblende, apatite, magnetite, and titanite from that rock and the secretion of those leached-out compounds in the

free spaces of the shear zones. The biotite was similarly segregated, but its mobility was found to be considerably less than that of the hornblende. If the metamorphism had been yet more energetic in the Osoyoos body, the more soluble compounds would have been carried away completely and the whole would have crystallized in the form of acid biotitic gneiss banded with especially micaceous schists in the zones of maximum shear. Such appears to the writer to be the best explanation of the Eastern phase of the Remmel batholith.

2. The composition of the rock and the fact that, as above mentioned, it seems to have been thoroughly recrystallized into a strong, well knit, banded gneiss without cataclastic structure agree with this view.

3. The conclusion is substantiated in the study of more moderate shearing in the Western phase itself. There the strongly granulated and not recrystallized granodiorite shows impoverishment in the more mobile hornblende and accessories, which are segregated into intercalated, recrystallized bands. Thus hornblende-free, crushed rock indistinguishable in composition from the rock of the Eastern phase occurs sporadically in many local areas within the normal crushed granodiorite of the Western phase.

In summary, then, the Remmel granodiorite, gneissic biotite granite, biotite gneiss, biotite quartz diorite, and hornblende gneiss appear to belong to a single batholithic intrusion. This mass was originally a typical granodiorite. It has been dynamically and hydrothermally metamorphosed with intense shearing in zones trending north 20 to 25 degrees west. Over most of the batholith so far investigated these zones of physical and chemical alteration are not so well developed as to obscure the essential nature of the primary magma (Western phase). The shearing and transformation are much more profound in a wide belt elongated in the general structural direction north 25 degrees west. Here the rocks are well banded biotite gneisses, the material of which is residual after the deep seated, wholesale leaching of the more basic mineral matter from the crushed granodiorite (Eastern phase).

KRUGER ALKALINE BODY

Characteristics.—All the way from the Great plains to the Pacific waters nepheline rocks are extremely rare on the 49th parallel of latitude. The boundary section is now so far completed that it can be stated that in the entire section the Kruger body is the only plutonic mass bearing essential nepheline; it is likewise the most alkaline plutonic mass.

One of its principal characteristics is great lithological variability. It varies signally in grain, in structure, and above all in composition. All the varietal rock types carry essential feldspars of high alkalinity—microperthite, microcline, soda-orthoclase, and orthoclase. Nepheline, biotite, brown-green hornblende, a pyroxene of the ægerine-augite series, and melanite complete the general list of essentials. Titanite, titaniferous magnetite or ilmenite, rutile, apatite, and acid andesine, Ab_5An_3 (the last entirely absent in most of the rock phases), form the staple accessories, though any one or more of the colored silicates may be only accessory in certain phases. Muscovite, hydronepheline, kaolin, calcite, epidote, and chlorite are secondary, but on account of the notable freshness of the rocks are believed to be due to crush-metamorphism more than to weathering.

According to the relative proportions of the essential minerals, at least ten different varieties of alkaline rock have been found in the body. These are—

Augite-nepheline malignite,
Augite-biotite-nepheline malignite,
Augite-biotite-melanite malignite,
Hornblende-augite malignite,
Augite-nepheline syenite,
Hornblende-nepheline syenite,
Biotite-melanite-nepheline syenite,
Augite-biotite-nepheline syenite,
Porphyritic augite syenite,
Porphyritic alkaline biotite syenite.

There is a question as to how far this list of varieties actually represents the original magmatic variation within the body. The evidence is good that the augite and hornblende and a part of the biotite, along with the feldspars and nepheline, crystallized from the magma. It is not certain in the case of melanite which, in the Ontario malignite, as described by Lawson, appears to be a primary essential.* Microscopic study shows that much of the melanite in the Kruger rocks is of magmatic origin, but that perhaps much more of it has replaced the pyroxene during dynamic metamorphism. In such cases the pyroxene, where still in part remaining, is very ragged, with granular aggregates of the garnet occupying the irregular embayments in the attacked mineral. A further stage consists in the complete replacement of the augite by the melanite aggregates which are shot through with metamorphic biotite. These peculiar reactions between the pyroxene and the other components of the rock are widespread in both syenite and malignite.

All the phases so far studied in this natural museum of alkaline types can be grouped in three classes—granular malignites, granular nepheline syenites, and coarsely porphyritic alkaline syenites. The malignitic varieties are always basic in look, dark greenish-gray in color, and medium to coarse in grain (specific gravity, 2.757 to 2.967). The nepheline syenites are rather light bluish-gray in tint, medium to fine grained, and break with the sonorous ring characteristic of phonolite (specific gravity, 2.606 to 2.719). The third class of rocks is much less important as to volume; they are always coarse in grain, of gray color, and charged with abundant tabular phenocrysts of microperthite which range from 2 to 5 centimeters in length. These phenocrysts as well as the alkaline feldspars of the coarse groundmass are usually twinned, following the Carlsbad law—a characteristic very seldom observed in the malignites or nepheline syenites.

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*Bulletin, Dept. of Geology, University of California, vol. 1, 190.

The nepheline syenites often send strong apophysal offshoots into the malignites, but such tongues are highly irregular and intimately welded with the adjacent basic rock as if the latter were still hot when the nepheline syenites were intruded. Moreover, there are all stages of transition in a single broad outcrop between typical malignite and more leucocratic rock indistinguishable from the nepheline syenite of the apophyses. Similarly, even with tolerably good exposures, no sharp contacts could be discovered between the coarse, porphyritic syenites and the other phases. The porphyritic rocks almost invariably showed strong and unmistakable flow structure, evidenced in the parallel arrangement of undeformed phenocrysts; these generally lie parallel to the contact walls of the body as a whole. The phasal variety of the Kruger body and the field relations of the different types seem best explained on the hypothesis that the phases are all nearly or quite contemporaneous—the product of rapid magmatic differentiation accompanied by strong movements of the magma. These movements continued into the viscous stage immediately preceding crystallization.

The average composition of the whole Kruger body is probably that of a malignite transitional into true nepheline syenite; its specific gravity, about 2.750.

Metamorphism.—Few of the specimens collected are free from signs of crushing. This has sometimes induced a decided gneissic structure, and almost always the microscope shows fracture and granulation. The abundant development of metamorphic melanite and biotite and the occasional production of large poikilitic scapolites indicate some recrystallization through dynamic metamorphism. The abundance of microcline and the generally subordinate character of the orthoclase is another, yet more familiar, relation brought about through the crushing. The mechanical alteration of these rocks is far from being as thorough as in the case of the Osoyoos batholith. This is a principal reason for believing that the alkaline mass was intruded after the Osoyoos granodiorite had been itself well crushed. No other definite field evidence for or against that view has been discovered. However, the magmatic relationships between the uncrushed Cathedral and Similkameen batholiths and the Kruger body also suggest that all three belong to one eruptive epoch of several stages—an epoch long subsequent to the intrusion of the Osoyoos and Remmel batholiths. The Similkameen granite is clearly intrusive into the Kruger alkalines, which may owe their strained and often granulated condition to the forceful entrance of that immense and immediately adjoining body of granite (see figure 3).

Three complete chemical analyses of types from the body have been made, which clearly show that the rare family of malignites is here represented on a large scale. The analyses are not given or discussed in this paper, as their details are scarcely relevant to the main purposes of the geological inquiry.

SIMILKAMEEN GRANITE BATHOLITH

General character and mineral constituents.—The staple rock of the Similkameen batholith is a medium to coarse grained, light pinkish-gray soda granite. Its essential constituents are hornblende, biotite, quartz, basic oligoclase (averaging Ab_7An_3), and the alkaline feldspars, microperthite, microcline, microcline-microperthite, and orthoclase. The last named is characteristically rare; microperthite is the most abundant of the alkaline feldspars. The accessories are magnetite, apatite, and beautifully crystallized titanite. Allanite is a rare accessory; epidote is occasionally present, but apparently is secondary. The structure and order of crystallization are normal for granites, though microperthite is often in phenocrystic development. A determination of the weight percentages of the constituents found in a type specimen collected in the Similkameen River valley was made by the Rosiwal method. It gave:

	Per cent
Oligoclase	29.8
Microperthite	27.0
Quartz	22.0
Orthoclase and microcline	6.7
Biotite	5.5
Hornblende	4.2
Magnetite	1.8
Titanite	1.1
Epidote	1.1
Apatite	.8
	100.0

This calculation is rough, though it gives a calculated specific gravity for the rock (2.682) that checks well with the observed specific gravity (2.693).

For many square miles together the great central portion of the batholith is composed of this rock—a soda-rich biotite-hornblende granite of an average specific gravity of 2.706.

At the head of Toude (or Toat) coulee the rock of a large area within the batholith is generally porphyritic and distinctly finer grained than the staple granite, the specific gravity averaging 2.675. The phenocrysts are poikilitic microperthites bearing many inclusions of the other constituents. In the specimens so far examined, orthoclase tends to dominate over microperthite. Near the contacts with the normal equigranular rock, oligoclase replaces the alkaline feldspars to a great extent; yet this phase is always poorer in both hornblende and biotite than the normal phase, which is thus slightly the more basic rock. The finer grained phase was seen at several places only a few feet from the coarser; the contact is there sharp, but the absolute relation between the two phases could not be determined. It is highly probable that both are of nearly contemporaneous origin, the intrusion of the porphyritic phase having followed that of the equigranular rock by a short interval, as if in consequence of massive movements in one slightly heterogeneous, partially cooled magma. The porphyritic phase often shades into the other so imperceptibly that a separation of the two phases on the map is a matter of great difficulty, if not of impossibility.

The material of the batholith is further varied by rather rare basic segregations, These have the composition of hornblende-biotite diorite, being made up of the minerals of earlier generation in the host.

Contact basification.—Much more important products of differentiation, as shown by microscopic analysis, are illustrated in a wide zone of contact basification. Here there occur several related types of alkaline or subalkaline syenites. In specimens collected along the contact with the Kruger alkalines, quartz nearly or altogether fails, biotite is absent, and abundant diopsidic augite accompanies the essential hornblende. The feldspars are the same as in the staple rock, with basic oligoclase, Ab_2An_1, yet more abundant than there. Zircon is added to the list of accessories. These facts and the general habit of the rock relate it both to monzonite and to genuine alkaline syenites. The chemical analysis closely resembles that of the typical rock from Monzoni, except that the soda is strongly dominant over the potash (4.60 per cent of Na_2O to 3.00 per cent of K_2O). This basic phase may be called an augite-hornblende soda monzonite of a specific gravity of 2.800–2.819. It is known to extend at least 1,200 yards from the main eastern contact of the batholith. It is an open question as to how far this basification is due to absorption of material from the adjacent malignite-syenite series and how far to ordinary spontaneous differentiation along the batholith walls.

On the contact with the quartzites and schists of mount Chopaka the basification is less pronounced; compared to the staple granite, this phase is poor in quartz and rich in oligoclase-andesine and hornblende. It may be called a hornblende-biotite soda monzonite of a specific gravity of 2.712–2.748.

For a half mile or more northwest of the contact with a large body of schist forming the Horseshoe pendant (figure 4) the batholith exhibits a third basic phase. There is an almost complete disappearance of alkaline feldspars, other characters of the rock remaining essentially like those of the granite. This phase is a hornblende-biotite quartz diorite of a specific gravity of 2.736. Here again there is doubt as to the exact cause of the basification. The Horseshoe pendant is largely amphibolitic in composition, and it is possible that assimilation of material from these schists is partly responsible for the development of the quartz diorite.

CATHEDRAL GRANITE BATHOLITH

Character of the material.—The youngest of the batholithic intrusives is petrographically the simplest of all. Its material is singularly homogeneous, both mineralogically and texturally. The rock is a coarse grained, light, pinkish-gray biotite granite of common macroscopic habit. The essential minerals are microperthite, quartz, oligoclase, Ab$_3$An$_1$, orthoclase, and biotite; the accessories, apatite and magnetite, with rather rare titanite and zircon. The order of crystallization is normal for granites. Sometimes, and especially along contact walls, the rock is porphyritic, with the microperthite developed in large idiomorphic and poikilitic phenocrysts, which, as described by Calkins, weather out with a retention of the crystal form.

A determination of weight percentages by the Rosiwal method afforded the following result:

	Per cent
Microperthite	40.3
Quartz	35.7
Oligoclase	11.0
Orthoclase	7.0
Biotite	5.0
Magnetite and titanite	.7
Apatite	.3
	100.0

It is seen by inspection of the weight percentage tables that this granite carries more silica than does the granite of the Similkameen batholith, which in its turn is more acid than the granodiorites.

The great bulk of the batholith is thus composed of biotite soda granite (specific gravity, 2.631).

A local varietal phase, bearing dark green hornblende as a second essential, was found in the contact zone, 400 yards or more in width, alongside the Similkameen hornblende-biotite granite; here there may also be some slight enrichment in oligoclase at the expense of the microperthite. Neither hornblende nor biotite is abundant. The specific gravity of this phase is 2.644. The cause of the basification must once more be left undecided; it may lie in assimilation, in differentiation, or in both.

The ordinary basic segregation is notably rare in this batholith. A few, with the composition of biotite quartz diorite, were seen, but they seldom exceeded a few inches in diameter.

Younger phase.—The coarse granite had been intruded, and apparently so far cooled that joints had developed within its mass, when a second eruptive effort thrust a great wedge of nearly identical magma into the heart of the batholith. This may be called the Younger phase of the Cathedral batholith. It forms a large dike-like mass 3½ miles long and averaging 400 yards in width; its length runs about north 60 degrees west and lies parallel to a system of master joint planes within the Older phase.

The Younger phase has the same general color as the coarse granite, but is finer grained, more regularly porphyritic, and more acid. The microperthite of the older granite is here largely replaced by orthoclase and microcline, both sodiferous; at the same time the plagioclase is more acid, being oligoclase near Ab_8An_1. The accessories are the same as in the coarse granite, but are much rarer. Biotite, too, is here less abundant. The weight percentages are approximately:

	Per cent
Quartz	38.8
Orthoclase and microcline	33.4
Oligoclase	17.6
Microperthite	5.8
Biotite	3.5
Magnetite	.6
Apatite	.3
	100.0

The Younger phase approaches an aplitic relation to the older. The contacts between the two were seen at several points; they are sharp, yet the two rocks are closely welded together, and it seems probable that the coarser granite was still hot when the younger granite was injected.

PARK GRANITE STOCK

The Park Granite stock measures 4 miles in length by 2½ miles in width (figure 6). This granite is coarse, unsqueezed, and in almost all respects resembles macroscopically the Older phase of the Cathedral batholith, of which the Park granite seems to be a satellite. Under the microscope the rock differs from the coarser Cathedral granite chiefly in the entire replacement of microperthite by orthoclase; so that this granite is a normal biotite granite rather than a soda granite. The greater homogeneity of the dominant feldspar may explain the fact that the Park granite is somewhat more resistant to the weather than the Older phase of the Cathedral batholith. A few prisms of dark green hornblende are accessory in much the same proportion as in the Younger phase of the Cathedral. With these exceptions, both essential and accessory constituents are, in individual properties and in relative amounts, practically identical in the type specimens of stock and the Older phase of the batholith. The specific gravity of the Park granite is 2.673.

A second, very small boss of the Park granite occurs within the mass of the Remmel batholith some 5 miles west-southwest of the Park Granite stock. This boss is circular in plan and measures not more than 250 yards in diameter.

GEOLOGICAL RELATIONS

The Okanagan mountains are among the most accessible in the whole trans-Cordilleran section along the 49th parallel. Even without a trail, horses can be taken to almost any point in the 5-mile belt. Owing partly to mere altitude, partly to the general climatic conditions, the summits are often well above the timber line, while the mountain flanks are clad with the woods of beautiful park lands. Another special advantage in determining geological relations consists in the freshness of the rocks, which have been heavily glaciated and have not been seriously injured by secular decay. With a little searching, excellent and often remarkably perfect exposures of every formation and of its more important contacts can usually be discovered. Each of the principal field relations now to be noted has been determined not from one contact alone, but through the accordant testimony of several favorable localities.

The oldest rocks within the batholithic area are the Kruger schists, with their associated basic intrusives, and the roof pendants of the Similkameen batholith (figures 2, 3, 4, 5, and 6). Without doubt these rocks are comparable in age to quite similar formations forming the eastern limit of the Okanagan Composite batholith as a whole. From the eastern contact of the Osoyoos batholith eastward for nearly 20 miles the rolling mountain slopes are chiefly underlain by an intensely folded, mashed, and metamorphosed group of quartzites and phyllites, in which there occur intercalations of ancient diabasic rocks with occasionally strong pods of semi-crystalline limestone. These rocks had been crushed and dynamically metamorphosed before the intrusion of the oldest component batholith of the Okanagan range. Again and again since that early period of metamorphism the same stratified formations have been gripped in the writhing paroxysms of Cordilleran revolutions. So extensive has been the crumpling, shearing, and overturning that it must ever remain a matter of the utmost difficulty to reduce the series to stratigraphic order. Within the belt covered by the Boundary Commission it has proved so far impossible to secure either a bottom or top to the series. Fossils entirely fail. All that can be said concerning the age of the metamorphosed sediments is that they are almost certainly Paleozoic. In many respects they have lithological characters like those of Carboniferous formations both in California and British Columbia. It is very possible that portions of the series are still older. From analogies drawn from better known regions in the Cordillera, it is believed that the basic intrusives of mount Chopaka and of the great schist-sediment area east of Osoyoos lake are likewise of Paleozoic age, though of course younger than the schists and quartzites which they cut.

Since the rocks of the Basic complex are crushed and metamorphosed in as extraordinary degree as any of the above-mentioned formations, the complex is regarded as a Paleozoic parallel to the Chopaka basic intrusives, though perhaps not strictly contemporaneous with the latter. For a reason already noted, the Ashnola gabbro is possibly to be correlated in age with the larger part of the Basic complex.

The mode of intrusion and therewith the structural relation of each of these basic masses to its original country rock can not be declared. In the case of two of them—the Basic complex and the Ashnola gabbro—not a fragment of the invaded formation has been found. It is, however, improbable that any of these bodies ever had batholithic dimensions. Their present isolated positions and the analogy of other similar gabbro-peridotite bodies in the Cordillera suggest that each of them was of relatively small size. The Chopaka body cross-cuts the bedding of the quartzites and schists. It may be in "chonolithic" relation to these—that is, it may be an irregularly shaped mass magmatically injected into the bedded rocks, but not, as with a true laccolith, following bedding planes.* The contacts are insufficiently shown to warrant any decision in the case. The Ashnola gabbro may similarly be the residual part of an injected body. That it was a comparatively small body is suggested by an apparent flow structure still preserved even in the medium grained facies of the gabbro. In a batholithic rock of that texture, fluidal arrangement of the minerals is very rare. The infinitely diverse composition and structure of the Basic complex much more clearly points to a non-batholithic origin. One imagines rather that the lithological and structural complication are in this case such as might appear at the deep-seated focus of an ancient volcanic area. The geological record has, however, been too largely obscured or destroyed that any of these hypotheses concerning the basic intrusives can be verified.

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*Cf. Journal of Geology, vol. xiii, 1905, p. 498.

One fact is certain, that all of the bodies are older than the granites by which they are surrounded. Their contacts with the granites are the sharpest possible; gabbro or peridotite is pierced by many typical apophyses of granite or granodiorite which has often shattered the basic rocks and isolated blocks which now lie within the basic body. Here there is no question of the gabbros being differentiation products from their respective granitic magmas, as so often described in the granodiorite batholiths of California.* There remains, secondly, the conclusion that these basic intrusives were probably not of batholithic size. They show that some time before the real development of the Okanagan Composite batholith began, a basic, subcrustal magma was erupted on a limited scale—possibly in the form of stocks, possibly in the form of chonoliths.

Undoubted batholithic intrusion began with the irruption of the granodiorites. The familiar phenomena of such intrusion are exhibited along the contacts of the Osoyoos batholith. For several hundred yards from the igneous body the phyllites have been converted into typical, often garnetiferous, mica schists. This collar of thermal or hydrothermal metamorphism would doubtless be yet more conspicuous if at the time of intrusion the Paleozoic series had not already been partly recrystallized in the earlier dynamic metamorphism of the region.

The Remmel batholith is, as we have seen, composed of granodiorite similar in original composition to the rock of the Osoyoos batholith. Fossiliferous Lower Cretaceous arkose sandstones, grits, and conglomerates overlie the Remmel unconformably. The materials for these rocks were in part derived from the secular weathering of the Remmel granodiorite, the weathering being accompanied by rapid deposition of the debris in a local sea of transgression. Arkose sandstones, which alone measure more than 10,000 feet in thickness, were thus deposited in a down-warped marine area just west of the Pasayten river. To furnish such a volume of sediment, there would appear to have been in the region, preferably to the eastward of the Pasayten, a much larger area of granitic rocks than is now represented in the Remmel and Osoyoos batholiths combined. It is possible, indeed, that at that time these two batholiths were part of one huge mass of granodiorite which largely occupied the site of what is now the Okanagan Composite batholith. Both Remmel and Osoyoos granodiorites have suffered profound metamorphism, so similar in its effects in the two rock masses that it may most simply be attributed to the same period of orogenic disturbance. The systematic parallelism of the shear zones in each batholith and the fair accordance in trends of the zones occurring in both batholiths suggest that there has been but one such revolutionary disturbance since the batholiths were irrupted. If this be true, the period is identical with the post-Lower Cretaceous epoch, when the Pasayten Lower Cretaceous was thoroughly folded and crushed into its present greatly deformed conditions in the Hozomeen range.

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*See many of the Californian folios issued by the U. S. Geological Survey.

The Osoyoos and Remmel batholiths are thus probably contemporaneous probably both post-Carboniferous and certainly pre-Cretaceous. It is best to correlate them with similarly huge bodies of granodiorite determined as Jurassic in California and southern British Columbia.

It should be noted that, since the Remmel granodiorite disappears under the cover of Lower Cretaceous at the Pasayten, 60 miles is the minimum width of the Okanagan Composite batholith.

In the latter part of the Jurassic the granodiorite batholith was uncovered by erosion, then down warped to receive a vast load of quickly accumulated sediments until more than 30,000 feet of the Pasayten Cretaceous beds were deposited in the area between the Pasayten and Skagit rivers. As yet there is no means of knowing how far this filled geosynclinal extended to the eastward, but it doubtless spread over most of the area now occupied by the Okanagan Mountain range.

The prolonged sedimentation was followed by an orogenic revolution that must have rivaled the mighty changes of the Jurassic. The Cretaceous formation was flexed into strong folds or broken into fault blocks in which the dips now average more than 45 degrees and frequently approach verticality. It was probably then that the Jurassic granodiorites were sheared and crushed into banded gneisses and gneissic granites essentially the same as the rocks now exposed in the Remmel and Osoyoos batholiths. No sediments known to be of later age than the Lower Cretaceous have been found in this part of the Cascade system; hence it is not easy to date this orogenic movement with certainty. Dawson has already summarized the evidence going to show that many, perhaps all, parts of the Canadian Cordillera were affected by severe orogenic stresses at the close of the Laramie period.* It is probable that the stresses were even greater along the Pacific coast than they were in the eastern zone, where the Rocky Mountain system was built. To this post-Laramie, pre-Eocene epoch the shearing of the granodiorites may be best referred.

We have seen that there are good reasons for considering the composite Kruger Alkaline body as younger than the granodiorites. It is clearly older than the Similkameen granite, as proved by the discovery of fine apophyses of the granite cutting the nepheline rocks. The Kruger body once extended some distance farther west over an area now occupied by the granite. The former, when first intruded, was an irregularly shaped mass without simple relation to its country rocks, the Paleozoic complex. The mode of intrusion was that of either a stock or a chonolith. In the first case the body was subjacent and enlarged downwardly; in the second case it was injected and its downward cross-section may have diminished. As with so many other instances, the contacts are too meagerly exposed to fix the true alternative. The nepheline syenite was in part injected into the nearly contemporaneous malignite. The common fluidal structure of these rocks also points to a mode of wedge intrusion more like that of dike or laccolith than like that of a stock. The Kruger body may thus represent a composite chonolith, but the problem of its style of intrusion must remain open. The date of the intrusion was post-Laramie. The alkaline magma may have been squeezed into the schists while mountain building progressed or after it had ceased. The crushing and incipient metamorphism of this body is on a scale more appropriate to the thrust resulting from the irruption of the younger Similkameen granite than to the more powerful squeezing effect of the post-Laramie mountain building.

True batholithic irruption was resumed in the replacement of schists, nepheline rocks, and possibly much of the granodiorite by the Similkameen batholith. This great mass is uncrushed, never shows gneissic structure, and has never been significantly deformed through orogenic movements.

The composite batholith received its last structural component when the Cathedral granite finally cut its way through Remmel granodiorite, Similkameen granite, remnant Paleozoic schists, and possibly through Cretaceous strata, to take its place as one of the most imposing geological units in the Cascade system. The field proofs are very clear that the Similkameen granite was solid and virtually cold before this last granite ate its way through the roots of the mountain range. See the large intrusive tongues cutting the schist pendant north of Horseshoe mountain, as illustrated in figure 4. The contacts between the two batholiths are of knife-edge sharpness. The younger granite, persisting in all essential characters even to the main contacts, sends powerful apophyses into the older granite, exactly as if the two batholiths were in age several geological periods apart. Both are of Tertiary age and bear witness to the tremendous plutonic energies set free in a late epoch of Cordilleran history. Quietly, but with steady, incalculable force, this youngest magma worked its way upward and replaced the invaded rocks. During the same time the satellitic Park granite was irrupted with the stock form and relations.

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*Bull. Geol. Soc. Am., vol. 12, 1901, p. 87.

Smith and Mendenhall have described a large batholith of "quartz monzonite or quartz diorite" (granodiorite?) intrusive into Miocene argillites at Snoqualmie pass in the northern Cascades and 100 miles southwest of Osoyoos lake.* This is one of the youngest batholiths yet described in the world. The more basic phases of the Similkameen batholith present similarities to the rock at Snoqualmie pass. It is thus possible that the Similkameen granite was irrupted in late Miocene or even in Pliocene time; the Cathedral batholith is yet more recent.

RÉSUMÉ OF THE GEOLOGICAL HISTORY

The stages in the petrological development of the Okanagan Composite batholith as it now exists may now be summarized. We begin with the oldest stage that is of importance in this particular history:

1. Intense metamorphism of Paleozoic and earlier formations (probably) in the late Carboniferous period, accompanied or soon followed by the intrusion of the Chopaka, Ashnola, and Basic Complex gabbros and peridotites in chonolithic (?) or other relations. Differentiation within these bodies.

2. In Jurassic time, batholithic irruption of the Osoyoos and Remmel granodiorites. Contact differentiation of quartz diorite in the former, at least.

3. Rapid denudation of the granodiorite batholiths in the late Jurassic; local subsidence of their eroded surface beneath the sea, there to be covered with a thick blanket of Cretaceous sediments which are in part composed of debris from the granodiorite itself.

4. At the close of the Laramie period, revolutionary orogenic disturbance, shearing and crushing the granodiorites and basic intrusives. In the former, development of strong crush-foliation and banding with the

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*Bull. Geol. Soc. Am., vol. 11, 1900, p. 223.

formation of new rock types, including biotite-epidote-hornblende gneiss, biotite-epidote gneiss, basic hornblende gneiss, biotite schist, hornblende schist, and recrystallized biotite granite-gneisses; in the basic intrusives, development of metagabbro and various basic (dioritic) gneisses and hornblendites. Simultaneous strong folding of the Cretaceous strata.

5. Either accompanying or following the post-Laramie deformation, the (chonolithic?) intrusion of the Kruger Alkaline body, which consists of nearly synchronous masses of nepheline syenite and malignite. In these at least ten different rock types, due in part to the splitting of an alkaline magma and in part to later rynamic metamorphism, have been recognized.

6. In Tertiary time the batholithic irruption and complete crystallization of the soda-rich Similkameen hornblende-biotite granite, its contact basification forming soda-monzonites and quartz diorites.

7. In later Tertiary time the batholithic irruption of the Cathedral biotite granite, Older phase, accompanied by the intrusion of the Park Granite stock, immediately followed by the injection of the Cathedral granite, Younger phase, within the body of the Older phase.

8. Removal by denudation of much of the cover over each intrusive body. Complete destruction of the Cretaceous cover except at the Pasayten River overlap. Certain dikes of olivine basalt injected into the Cathedral and other granites are apparently of Pleistocene age and represent the latest products of eruptive activity in the Okanagan range. These dikes are quantitatively of no importance in the development of the composite batholith itself.

Sequence of the eruptive Rocks

The summary has been recast so as to show more conveniently the order in which the various intrusions took place. The resulting table also contains a column showing the average specific gravity of the rock composing each eruptive body. These values, as is the case with all values given in this paper, were obtained by the use of entire hand specimens varying in weight from a half pound to two pounds. A large, sensitive bullion balance was found to be specially adapted to the purpose. This method has several advantages over rapid methods in which only small rock fragments are used. The larger the specimen weighed, the greater is the probability that the average density is secured and the smaller the chance for error through adhering air bubbles. A third reason for preferring this method is that the shape of a trimmed hand specimen need never be impaired in obtaining the rock chip usually employed for specific gravity determinations.

The observations were made at room temperatures:

Geological age.	Stage of intrusion.	Name of body.	Observed variation in specific gravity.	Average specific gravity.
Late Paleozoic (Carboniferous?)	1*a*.	Chopaka basic intrusives.	Gabbro, 2.959... Dunite, 3.173....	3.074
	2.	Ashnola gabbro	2.935-2.957.......	2.946
	1*b*.	Basic complex (metamorphosed).	2.766-ca. 3.100....	2.872
Jurassic............	3*c*.	Osoyoos Granodiorite batholith (metamorphosed).	2.692-2.939.......	2.746
	3*a* and 3*b*.	Remmel Granodiorite batholith; two principal phases due to metamorphism.	2.655-2.680...	2.720
Close of the Laramie, or Tertiary.	4.	Kruger Alkaline body.	Malignites, average 2.824. Syenites, average 2.675.	2.750
Tertiary............	5*a* and 5*b*.	Similkameen Granite batholith; two principal phases.	2.660-2.819.......	2.706
	6*a*.	Cathedral Granite batholith, Older phase.	2.621-2.644......	2.631
	6*b*.	Park Granite stock.....	....	2.673
	7.	Cathedral batholith, Younger phase,	....	2.608

Magmatic stages 1*a* to 3*b*, inclusive, afforded non-alkaline rocks rich in hornblende and carrying plagioclase, either basic or of medium acidity, as the dominant feldspar. These bodies may be regarded as belonging to one consanguineous series. Magmatic stages 4 to 7, inclusive, afforded alkaline rocks bearing nepheline in the most basic phases and microperthite (orthoclase in 6*b* and 7) as the dominant feldspar throughout the series except in certain basified contact zones. This group belongs to a second consanguineous series. Each series shows a steady increase of acidity and decrease of density as its different members were successively intruded. With the exception of one abnormal stage, the same double law underlies the entire magmatic succession. This exception is found in the Kruger Alkaline body, which in almost every other respect as well is anomalous among these masses. The comparatively small size and the isolation of the nepheline-rock body and its structural characteristics and relations appear to warrant the conclusion that it is the product of a very special differentiation. Neither malignite nor nepheline syenite seems to represent a *general* subcrustal magma in the region at any time. It is different with the small bodies of gabbro in the roof pendants of the batholiths. The repeated occurrence of gabbro, not only in the Okanagan range, but throughout the length and breadth of the Cordillera, as throughout mountain ranges all over the world, signifies the strong probability that the bodies now occurring as the Chopaka, Ashnola, and Basic Complex intrusives emanated from a general basic *couche* underlying the mountain range.

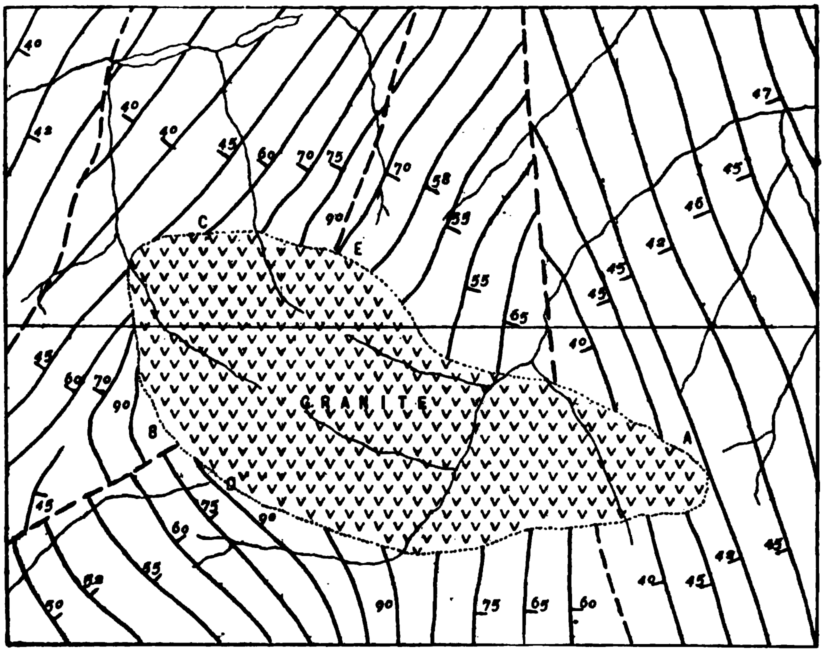

Figure 7.—*Ground Plan showing Relations of the Castle Peak Granodiorite to the deformed Pasayten Formation.*

Strike and dip lines in solid black; faults in broken lines. Figures show values of dip. Scale, 1 : 115,000.

Excluding the Kruger Alkaline body, then, it is seen from the table and from the petrographical descriptions that both of the respectively consanguineous series belong to a still greater series forming one petrogenic cycle. In this cycle the law of increasing acidity and diminishing density of the materials successively irrupted and crystallized is rigidly followed.

For a new reason, therefore, it is profitable to regard the many intrusive bodies as forming a single composite batholith. Favoring that concept, the chemical and physical nature of the unit masses, systematically variable as these are, and the general geological structure of the Okanagan Range alike command attention. To the petrographical systematist the inclusion of such rocks as peridotites and gabbros with nepheline syenites and malignites may be like classifying bats with birds, but the geological and even genetic connection of both alkaline and non-alkaline types is here manifest.

NATURE OF BATHOLITHIC INTRUSIONS

REPLACEMENT THEORY AND ILLUSTRATION

Year by year the conviction has been growing ever stronger in the minds of many able geologists that such a batholith as any one of those here described has assumed its present size and position by actually replacing an equal or approximately equal mass of the older solid rock. The Okanagan Composite batholith repeatedly illustrates this truth. The writer is frankly unable to conceive that the huge Cathedral batholith, for example, could have been formed by any process of simple injection without leaving abundant traces of prodigious rending and general disorder in the

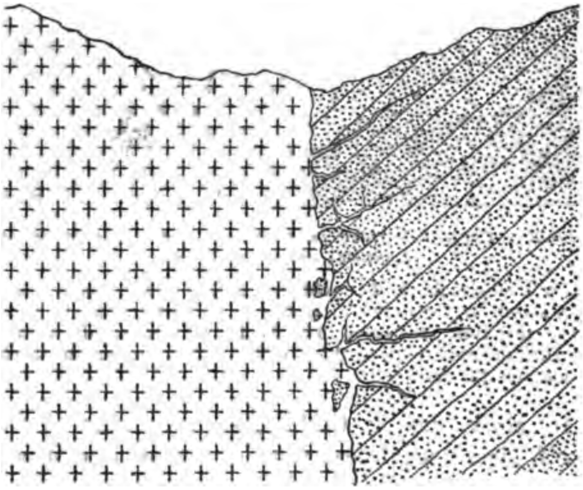

FIGURE 8.—*Contact Surface between the Castle Peak Granodiorite and tilted Cretaceous Sandstones and Argillites.*

The section is shown in the wall of a glacial cirque at the eastern end of the stock, the point marked "A" in figure 7. Scale, 1 inch to 175 feet.

granites alongside. We have seen, on the contrary, that the Similkameen granite on the east is notably free from such records of orogenic turmoil, while the shear zones of the Remmel batholith on the west most probably antedate the Cathedral granite intrusion. The very scale of these great bodies is suggestive of bodily replacement; it is hard to visualize an earth's crust which would so part as to permit of the laccolithic or chonolithic injection of a mass as great as a batholith.

The general absence of bedded rocks into which any one of the batholiths was irrupted means that some of the usual criteria of replacement can not be applied. It is therefore a matter of special importance that a small Tertiary stock, such as Castle peak, a satellite of the composite batholith itself, gives unequivocal proof of the doctrine of batholithic replacement.

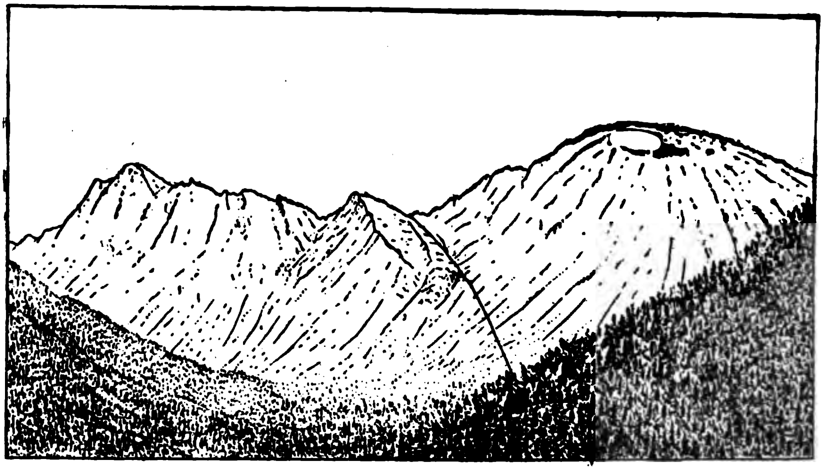

FIGURE 9.—*Plunging Contact Surface between intrusive Granodiorite and Cretaceous Argillites and Sandstones.*

Drawn from a photograph of the west end of the Castle Peak stock. View looks south. Contact shown by heavy line in middle of view; the point "B" in figure 7 is at the upper end of this line. Intrusive granodiorite on left, argillites and sandstone on right. The vertical distance between the two ends of the contact line as drawn is 1,500 feet. Castle peak on the left.

The Castle Peak stock, which covers 10 square miles in area, is located on the divide between the Pasayten and Skagit rivers, in the rugged crest of the Hozomeen division of the Cascade range. The peak is the highest of a group of noble mountains lying wholly or in part within this small plutonic area. This igneous body is composed of typical granodiorite with a strong basified contact zone of hornblende-biotite quartz diorite. The area and ground plan of the stock are shown in figure 7. The country rocks are Cretaceous argillites and sandstones, so folded and faulted as to present dips varying from 40 to 90 degrees. Lines of strike and characteristic dips are illustrated in the diagrammatic map.

It can be seen from the map that the stock is not in laccolithic relations; but only in the field, as one follows the wonderfully exposed contact line, does one appreciate the fullness of the evidence that the plutonic mass is a cross-cutting body in every sense. Even where the contact line locally coincides in direction with the strike of the sediments, as at the eastern end of the stock, the dipping strata are sharply truncated by the

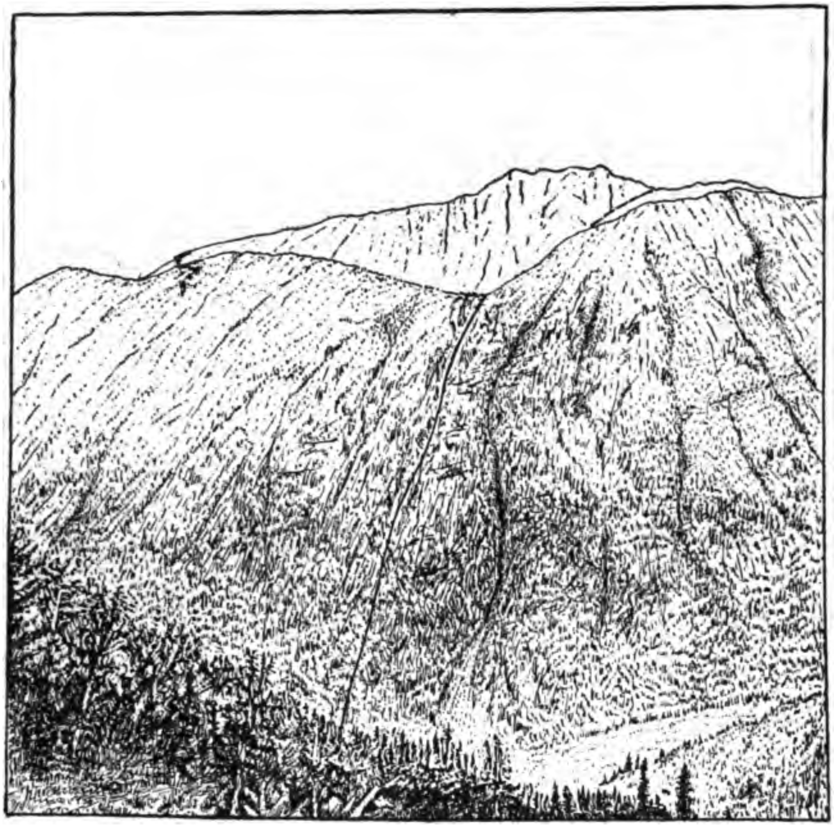

FIGURE 10.—*Plunging Contact Surface between intrusive Granodiorite (on the right) and Cretaceous Formation (on the left).*

Drawn from a photograph taken on the north side of the Castle Peak stock, near the point "C," figure 7. View looking east. Contact shown by heavy line in middle of view. Granodiorite on right and Cretaceous formation on left. The vertical distance between the two ends of the contact line as drawn is 1,700 feet; contact also located in the background with broken lines.

granodiorite (figure 8). Moreover, the granodiorite was not introduced by any system of cross-faults or peripheral faults dislocating the sedimentary rocks. Owing to the special attitudes of the latter, the strike and dip of the beds would be peculiarly sensitive to such dislocation. The faulting actually displayed in the Cretaceous beds is strike faulting and was completed before the granodiorite was intruded (figure 7). The igneous body is thus neither a bysmalith nor a chonolith. The magma entered the tilted sediments, quietly replacing cubic mile after cubic mile until its energies failed and it froze *in situ*.

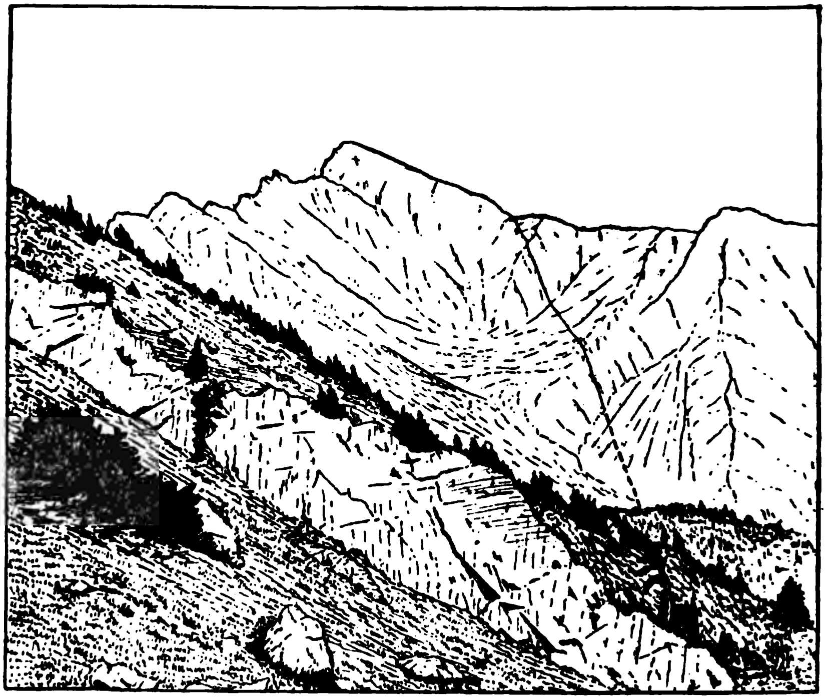

FIGURE 11.—*Plunging Contact Surface between intrusive Granodiorite and Cretaceous Formation.*

Drawn from a photograph taken on the south side of the Castle Peak stock, near the point "D," figure 7. View looking east. Contact shown by heavy line, right center of view. Granodiorite on left, Cretaceous formation on right. The vertical distance between the two ends of the contact line as drawn is 800 feet. The highest summit is Castle peak.

Not only so; the superb exposures seen at many points in the deep canyons trenching the granodiorite illustrate with quite spectacular effect the downward enlargement of the intrusive body. At both ends and on both sides of the granodiorite body the steep mountain cliffs exhibit the intrusive contact surface through vertical depths of from 300 to 2,200 feet. In every case the contact surface dips away from the granodiorite, plunging under sandstone or argillite and truncating the beds. The angle of this dip varies from less than 20 degrees to 80 or 85 degrees (figures 9, 10, 11, and 12). On the north side of the granodiorite a section of the domed roof of the magma chamber still remains (figure 12). It is noteworthy that a well developed system of rifts or master joints in the granodiorite seems, with its low dip, to be arranged parallel to the north sloping roof, as if due to the contraction of the igneous rock on losing heat upward by conduction.

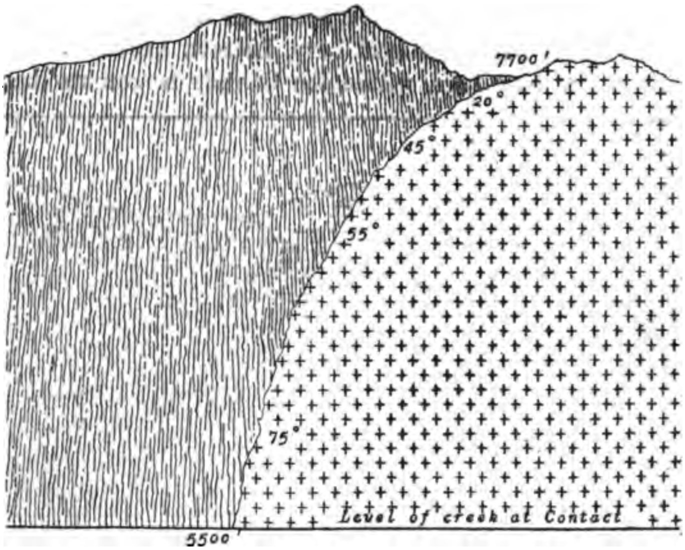

FIGURE 12.—***Intrusive Contact between Granodiorite and nearly vertical Cretaceous Argillites.***

Sketched in the field, on the north side of the Castle Peak stock, and seen in the wall of a deep canyon near the point "E," figure 7. Granodiorite on right and argillites on left.

This fact of downward enlargement makes it still more surely impossible to conceive that the granodiorite was injected into the sediments by filling a cavity opened by orogenic energy. A visible section even 2,200 feet deep does not prove the continuance of downward enlargement with depth; yet there is no logical reason to doubt that at least the steeper observed dips of the igneous contact surface are but samples of its dips for several miles beneath the present land surface. Moreover, if the granodiorite made its own way through the stratified rocks and was not an injected body, passively yielding to ordinary orogenic pressures, there must have been free communication between the now visible upper part of the magma chamber and the hot interior of the earth. Downward enlargement is not only proved in visible cliff sections; it is demanded as a necessary condition of heat supply during spontaneous intrusion.

The Castle Peak plutonic body thus appears to be a typical stock, an intrusive mass (*a*) without a true floor, (*b*) downwardly broadening in cross-section, and (*c*) intruded in the form of fluid magma, actively, though gradually, replacing the sedimentary rocks with its own substance. It is the most ideally exposed stock of which the writer has any record.

BATHOLITHIC INTRUSION BY MAGMATIC REPLACEMENT

Without needing to revert to the accordant discoveries of masters in geology—of Suess, Barrois, Michel Lévy, Lacroix, Lawson, Dawson, and many others—we have here, within the Cascade mountains themselves, illustrations of magmatic replacement. These authors believe, further, that a stock like Castle peak is but a small batholith; that several associated stocks may be in truth but protuberant parts of one subcrustal plutonic mass, which with further unroofing would declare itself a typical batholith. These views are consistently upheld by every pertinent structural detail that has yet been made out in the units of the composite batholith. Where bedded rocks still remain, they are cross-cut by the granitic bodies. Excellent exposures show that the contact surfaces of the Similkameen granite with the Chopaka Mountain and Snowy Mountain schist pendants dip underneath the invaded rocks, proving with every exposure seen the downward enlargement of the batholith (figures 13 and 14). In

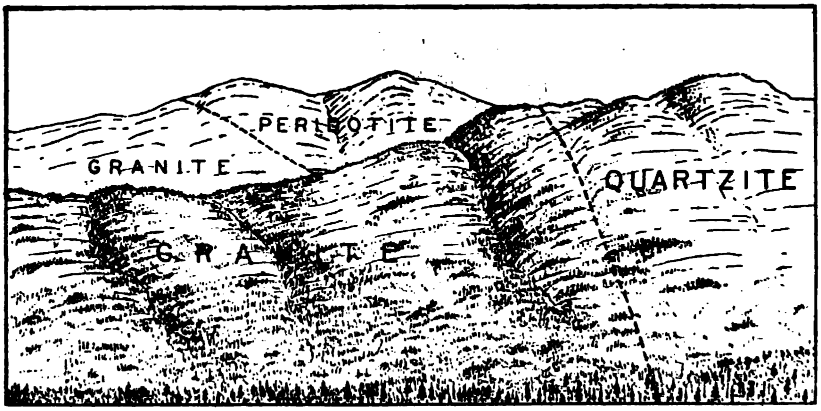

FIGURE 13.—*Plunging intrusive Contact Surface between the Similkameen Granite and the Chopaka Roof Pendant.*

Contact shown in broken lines. The vertical distance between the two ends of the contact seen on nearer ridge is 1,600 feet. Drawn from a photograph. Looking east.

one section more than half a mile in length the granite can be seen actually underlying a large section of the Snowy Mountain pendant.

In short, the fact of magmatic replacement and the related fact of downward enlargement of the great magma chambers seem to be well established. So fundamental are these facts that their evidence has been presented somewhat at length and with considerable illustration.

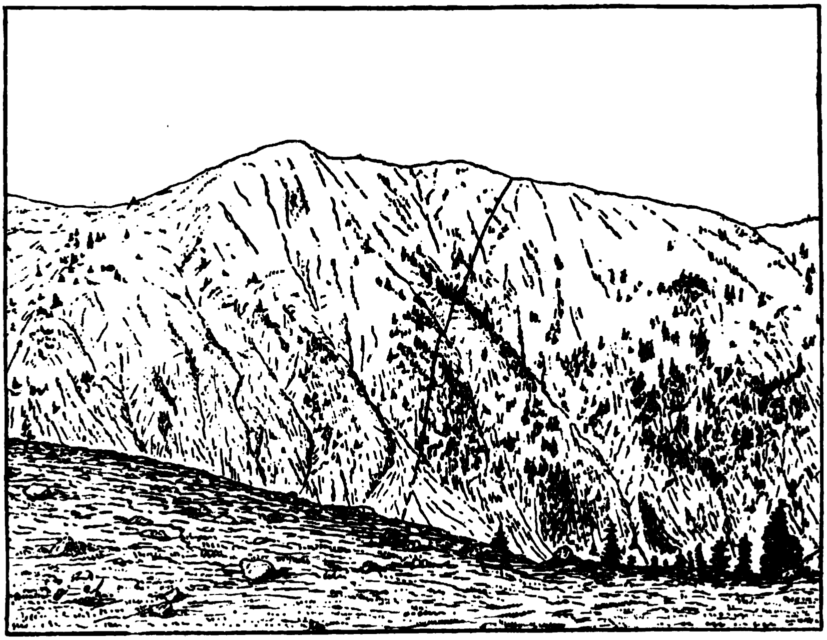

FIGURE 14.—*Outcrop of the intrusive Contact Surface shown in Figure 13.* The vertical distance between the two ends of the contact line as drawn is 1,100 feet. The granite is on the right; quartzite and schist on the left. Drawn from a photograph. Looking west.

METHODS OF MAGMATIC REPLACEMENT; THE ASSIMILATION-DIFFERENTIATION THEORY

The chief petrologic problem consists in discovering the essential processes engaged in the magmatic replacement. In several publications the writer has treated of the various solutions of the problem.* On account of their complexity, the data for the best solution, attributing the replacement of the invaded formation to magmatic assimilation, may not here be stated in full. A very brief outline must suffice. Magmatic assimilation is regarded as of a double sort, consisting, first, of the progressive fusion of main contact walls by original hot magma aided by its water and other solvents; secondly, of the progressive stoping of blocks (xenoliths) from the roof and walls of the batholith or stock, followed by the abyssal solution of the xenoliths in the hot interior of the magmatic body. Systematic differentiation of this new, widely extended, subcrustal, compound magma accompanies and follows the assimilation. The principal cause of differentiation has been sought in gravitative adjustment stratifying the magmatic *couche* according to the law of upwardly decreasing density (meaning, in general, increasing content of silica from below upward in the magmatic strata). A subordinate cause of differentiation commonly develops basified contact zones by the diffusion of basic materials to the surfaces of cooling. In the nature of the case, this latter kind of differentiation belongs to the late magmatic period immediately preceding crystallization; and, as illustrated in the Castle Peak stock and the Similkameen batholith, appears to form a basified zone along the roof as well as along the walls.

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*American Journal of Science, vol. 15, 1903, p. 269; vol. 16, 1903, p. 107; vol. 20, 1905, p. 185.

Partly for that reason it has proved impossible to discover a law of increasing density with depth in the Similkameen granite. A series of fifteen fresh specimens of the rock were collected at altitudes varying from 1,200 to 8,050 feet above sea, and their specific gravities were carefully determined. The difference between the densities of specimens taken near or at the two extremes of vertical distance was found too small to allow of a definite conclusion, though the difference, small as it is, favors the law of density stratification. It must be remembered, however, that the concentration of volatile matter, such as water vapor, dissolved in the magma but largely expelled during crystallization, would possibly be greatest at the roof. The specific gravities of the crystallized rocks may therefore not afford direct values for the total density stratification during the fluid state of the magma. Then, too, the observed relative uniformity of the Similkameen granite is a function of the scale of the subcrustal magma *couche*. It was unquestionably very thick; strong density differences are probably not on any hypothesis to be expected in a vertical section less than several miles in depth.

The objection has very often been made to the idea of extensive assimilation that signs of actual digestion about blocks broken off from roof or wall commonly fail. This is, however, just what would be expected on the stoping hypothesis. The very position of such a block shows that at the time when it was broken off it was floated in a magma too toughly viscous to allow the block either to rise or sink. Under those conditions the solvent or assimilative power of the magma is at or near its minimum. In other words, contact decrepitation persists some time after contact fusion—the shatter period is longer than the fusion period. In a valuable paper on granites in New South Wales, Andrews has very clearly stated the case. Speaking of the New England batholiths, he says:

> **What we see are necessarily end reactions in the abyssal laboratories; for, however powerful the youthful stage of the invasion may have been, the present contact areas must represent the *dying struggles* only of the rising mass, since at these spots the intruding massif had no longer any *energy* left to replace the invaded rocks. Errors have often crept in, in the author's opinion, concerning the idea of rock assimilation through the lack of comprehension of this fact. For if weak, dying reactions give such results as one can see along the "blue granite" and later acid massif contact at Bolivia; along the Gympie slate and acid granite junction at Cow Flat; as also in the slates at Undercliffe, of what tremendous potency must such action have been possessed during its maximum strength, to wit, its youth or maturity.***

The reality of the shattering is abundantly, often dramatically, evident on most of the batholithic and stock contacts seen in the Boundary belt.

The leading question remains as to the nature of the original magma whose energies have effected the batholithic invasion. In the papers already cited the writer has shown reasons for believing that the initial magma in a complete petrogenic cycle is gabbroid, and thus basic in character. As so often pointed out by many authors, this magma is of such wide distribution that it seems to be original in the constitution of the earth. Its liquefaction, as with all plutonic magma, is doubtless consequent upon mountain-building disturbances. Given strong liquefaction, assimilation and batholithic intrusion automatically result.

It is clear that magma may be similarly formed by the abyssal fusion of sediments or schists through the rising of isogeotherms. That this of itself is not the explanation of most batholiths and stocks is disproved by the identity of material in contemporaneous bodies, though these respectively cut formations of quite different chemical composition. Simple fusion in place is also rendered improbable by the general sharpness of batholithic and stock contacts and by the manifestly exotic character of such a mass as the Castle Peak stock.

The original magma of the Okanagan Composite batholith may, as already noted, have been gabbro, now represented in the small intrusive (injected?) bodies occurring in the roof pendants. The Osoyoos and Remmel granodiorites resulted from the assimilation of Paleozoic and other old, relatively acid formations by the original magma. The Similkameen batholith must also include material won from the older granodiorites; and the Cathedral batholith, with its satellites, is a still later product, assimilating all the earlier formations, including possibly Cretaceous arkoses. Special differentiation at various times produced the Kruger Alkaline body and some of the dikes cutting the batholiths. In each irruptive epoch the crush of mountain building may have facilitated the liquefaction of the deeper lying portions of the invaded formations. Whatever the source of the heat, it was each time present in sufficient quantity to enable the magma of that stage to stope and dissolve its way upward, well into formations that were *not* fused through orogenic crushing. To that extent the magmas were superheated.

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*E. C. Andrews: The geology of the New England plateau, etc., Records Geological Survey N. S. Wales, 1905, vol. 8, p. 19.

The assimilation-differentiation theory thus explains the sequence of the irruptions forming the Composite batholith. At each intrusive stage the magma set free to eat its way upward was more basic than the average of the rock invaded. At each stage a new magma, the one actually in contact with the invaded formations, was generated through absorption and gravitative differentiation, and the silica of the new magma was higher than that of the preceding batholithic magma. The increasing acidity is a function of the density, which decreases from below upward in the subcrustal magma *couche*. This law of density is preserved in the specific gravities of the batholithic rocks as now crystallized.

SKELETON HISTORY OF A BATHOLITHIC MAGMA

The development of any one of the batholiths may be summarized as follows:

1. A period of high liquidity, conditioned by orogenic movement. This period is characterized by—

a. Contact fusion;

b. Stoping and abyssal assimilation of xenoliths, progressive modification (here acidification) of magma;

c. Injection of wide ranging apophyses;

d. Gravitative differentiation of the compound magma of assimilation;

e. Possibly the beginning of basic segregation.

2. A period of strong and increasing viscosity—a period characterized by—

a. Cessation of magmatic digestion;

b. Some subsequent continuation of contact shattering;

c. Completion of the observed segregation of basic materials in nodules and contact zones; development of maximum acidity in the main body of the batholith;

d. Crystallization of the mass during a viscous condition approaching that of a solid solution.*

GENERAL SUMMARY

1. At the 49th parallel of latitude the Okanagan mountains and a part of the belt of the Interior plateaus (the Interior plateau of Dawson) have been carved by erosion out of an assemblage of plutonic igneous rocks which, in spite of the diverse lithological character of the rocks, should be regarded as an enormous single member of the Cordilleran structure. This plutonic group is named the Okanagan Composite batholith. The details of its constitution are given in a foregoing résumé of its geological history.

2. This composite batholith was of slow development, beginning with small intrusions in late Paleozoic (or possibly Triassic) time, increased by great batholithic irruptions of granodiorite during the Jurassic, and completed by likewise immense irruptions of alkaline hornblende-biotite granite and biotite granite—batholiths of Tertiary age, possibly as late as the Upper Miocene or the Pliocene. The satellitic Tertiary stock of Castle peak in the Hozomeen range, is composed of normal granodiorite.

3. The local intrusion of a small, composite body of malignites and nepheline syenites; the regular basification along the batholith and stock contacts, giving collars of monzonites and diorites; and the sporadic appearance of certain peridotites (hornblendites and dunites) are probably all incidents of magmatic differentiation and do not directly represent the compositions of general subcrustal magmas.

4. The composite batholith and the Castle Peak stock offer striking testimony to the probable truth of the assimilation-differentiation theory of granitic rocks. A very brief summary of this theory is given above in the form of a skeleton key to the history of a batholithic magma.

5. The composite batholith includes two consanguineous series of intrusions. The older one is non-alkaline; the younger, alkaline. They are separated in time by the whole Cretaceous period, at least.

6. The two consanguineous series nevertheless appear to belong to one petrogenic cycle. Throughout the cycle batholithic intrusion has followed the usual law of decrease in magmatic density and increase of magmatic acidity with the progress of time.

7. Exposures of contact surfaces in the Castle Peak stock and in the Similkameen batholith illustrate with remarkable clearness the downward enlargement of such bodies with depth.

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*Cf. Brauns, Chemische Mineralogie. Leipsig, 1896, p. 97.

8. The Similkameen granite bears three roof pendants. Their distribution suggests that the present erosion surface of this batholith west of the Similkameen river is not far from coinciding with the constructional, subterranean surface of the batholith.

9. The Osoyoos and Remmel granodiorites have been extensively metamorphosed by orogenic crushing and its attendant processes. The metamorphism was both dynamic and hydrothermal. The granodiorites have been locally, though on a large scale, transformed into banded gneisses and schists. These changes have been brought about through the hydrous solution and migration of the original mineral substance of the granodiorites, especially the more basic minerals. The dissolved material has been leached out from the granulated rock and has recrystallized in strong shear zones to which the solutions have slowly traveled. The shearing and metamorphism probably began at a time when the Remmel batholith was buried beneath at least 30,000 feet of Cretaceous strata.

10. The intensity of this metamorphism and the development of the great Tertiary batholiths agree with other facts to show that post-Jurassic mountain building at the 49th parallel was caused by much more powerful compression than that which is shown in the broader Cordilleran zone passing through California; there the Jurassic batholiths are relatively uncrushed and Tertiary batholiths seem to be lacking.

11. The problems of the Okanagan Composite batholith illustrate once again, and on a large scale, the utmost dependence of a sound petrology upon structural geology. A suggested chief problem involves the relation of mountain-building to the repeated development of large bodies of superheated magma only a few miles beneath the surface of the mountain range. The fact of this association is apparent; its explanation is not here attempted.

R. A. Daly

WITH THE COMPLIMENTS OF THE WRITER.

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VARIOLITIC PILLOW-LAVA FROM NEWFOUNDLAND.

REGINALD A. DALY.

From the American Geologist, August, 1903.

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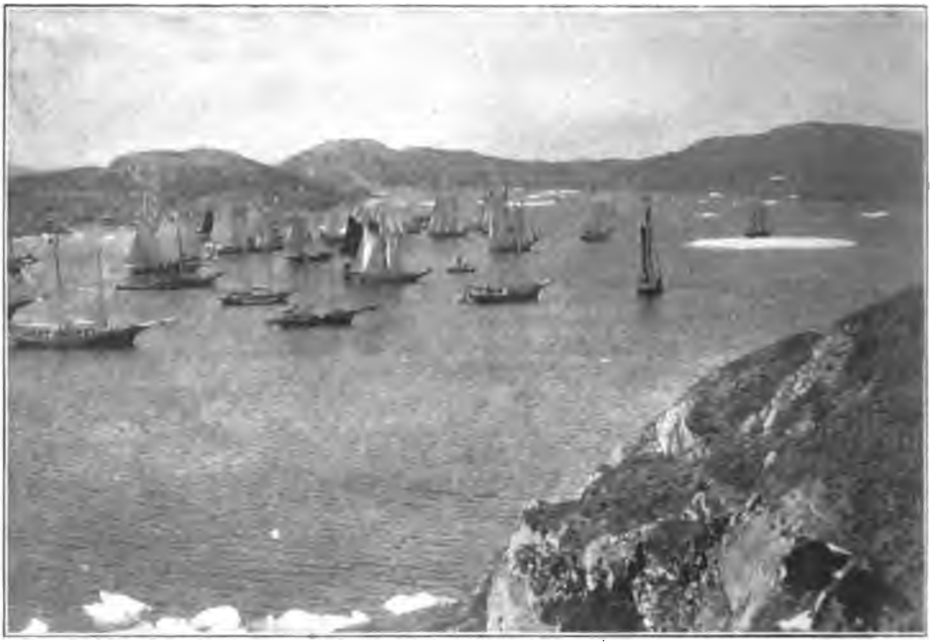

FIG. 1. (See p. 77.)

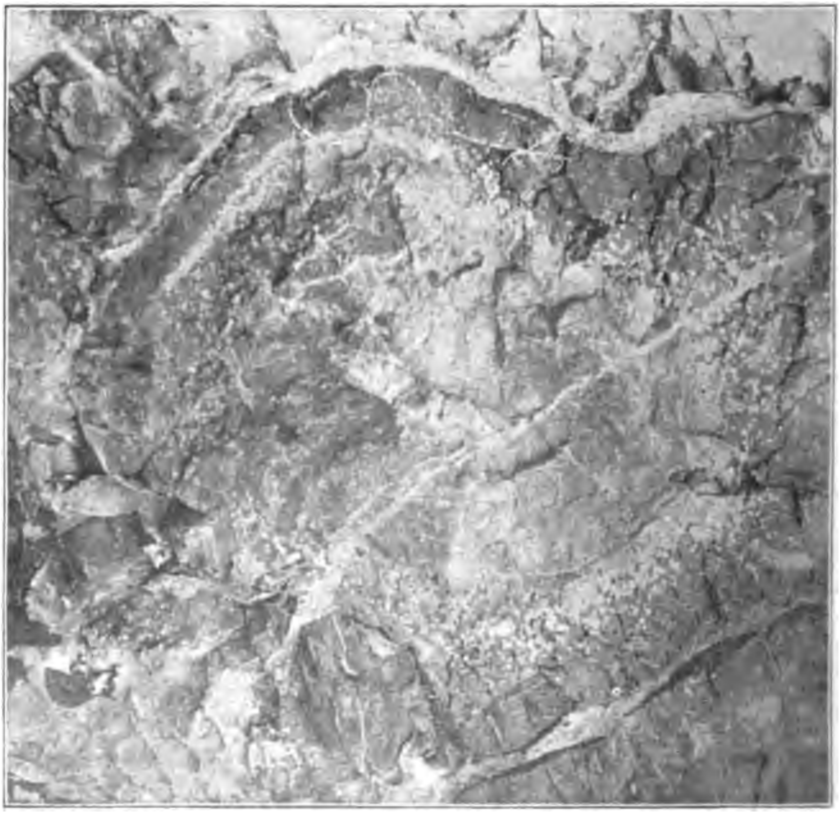

FIG. 2. (See p. 77.)

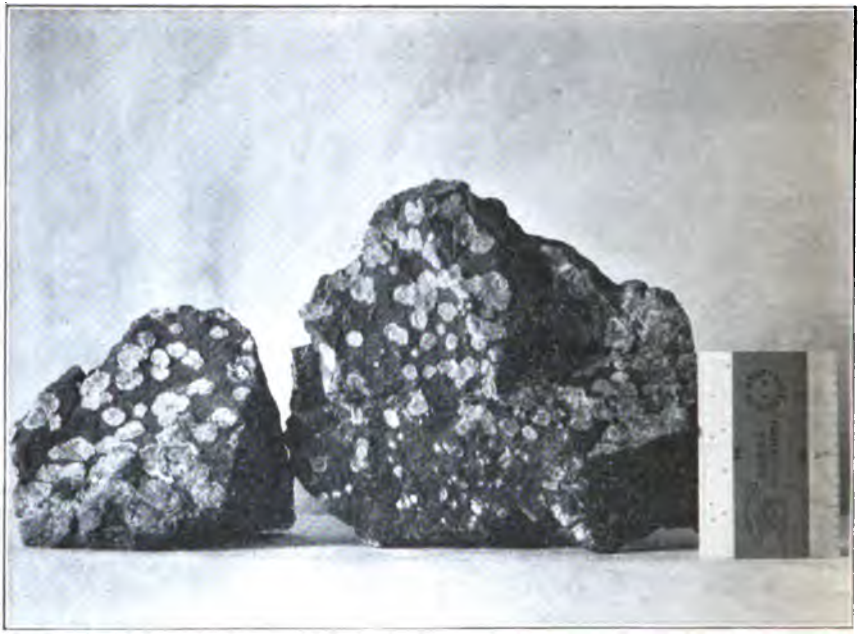

FIG. 3. (See p. 77.)

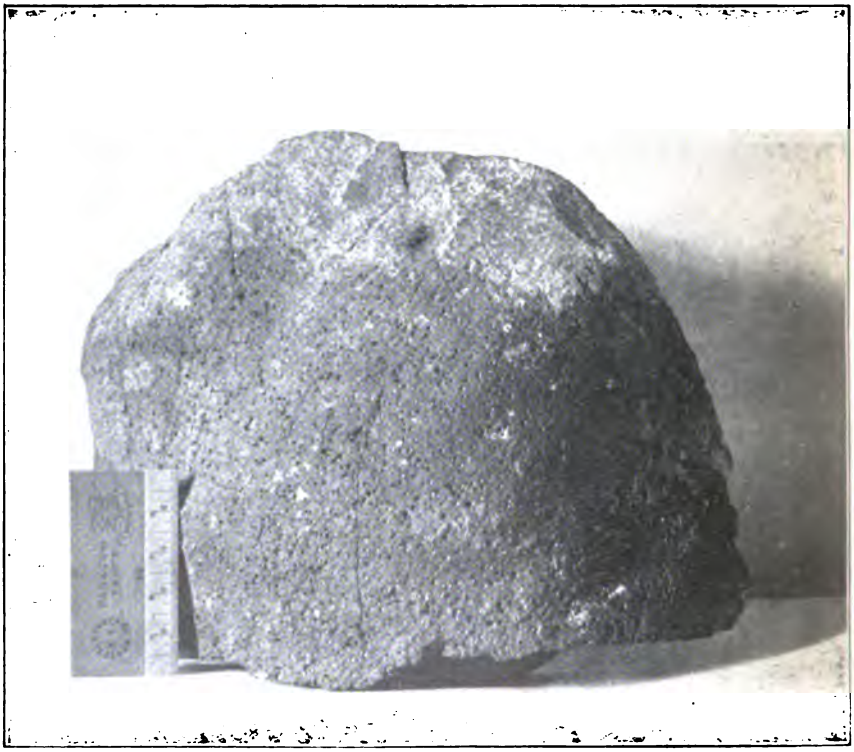

FIG. 4. (See p. 77.)

[*From The American Geologist, Vol. XXXII, August 1903.*]

VARIOLITIC PILLOW-LAVA FROM NEWFOUNDLAND.

By REGINALD A. DALY.

PLATES XIV-XV.

Introduction.—During the last few years there have been reported a considerable number of localities where "pillow-basalt" is to be found. The peculiar structure and stratigraphic relationships and, in several of the regions, the important volume of the rock partly explains the interest with which each new discovery has been received. The origin of the structure has also offered a problem that has aroused the keen attention of many geologists engaged in the study of the igneous rocks. Under the name of "agglomerates," "concretionary dolerite," "spheroidal basalt" or "ellipsoidal basalt," this rock has been discovered and described by workers in Minnesota, New Brunswick, California and Michigan. In the California and Michigan occurrences the lava is sometimes, though rarely, variolitic. The other known examples of pillow-lava have been found in Europe; in some of these, the variolitic habit is pronounced. So relatively limited is the total number of occurrences of both pillow-structure and variolitism in lava, that the discovery in Newfoundland of well-exposed deposits with both these features, seems worthy of record. In the following pages a brief description is therefore given of the new occurrence of this interesting and rather rare rock.

Field relations.—In the summer of 1900, the writer, as a member of a schooner expedition to Northern Labrador, was detained because of drift-ice and head-winds, in Kirpon Harbor near Cape Bauld at the extreme northern point of Newfoundland.* Short trips from the vessel on the mainland and on the adjoining islands led to the finding of pillow-lavas interbedded at several points with greatly cleaved and broken slates and sandstones. (Fig. 1 and Plate I, Fig. 1.) A deposit on Jacques Cartier Island is the best exposed, and, on account of its nearness to the schooner, could be studied in the greater detail. The description will hence refer more specifically to this one locality. The same general relations and petrographical characters, however, belong to the lava at the other localities, Kirpon Island and Fortune Bay.

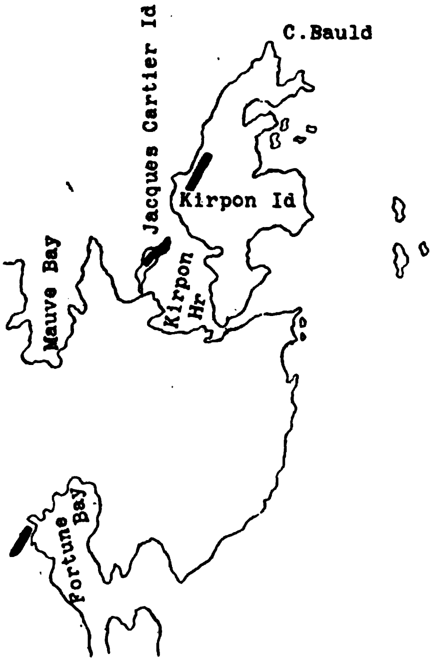

FIGURE 1.—Sketch-map showing location of the three occurrences of pillow-lava (heavy black lines) in northern Newfoundland.

The most favorable spot for determining the nature of the deposit was found at the ragged cliffs on the west side of the northern "tickle" or channel affording entrance to Kirpon Harbor. A long, deep chasm running parallel to the strike of the beds has there been worn out by wave-action. An excellent exposure has thereby been given of the pillow-lava and of the underlying formation. The latter consists of black and dark gray slates with alternating dark gray sandstones and grits which form part of the normal sedimentary series underlying islands and mainland. In these no fossils were to be found but the formation is doubtless part of a lower Palaeozoic terrane and perhaps equivalent to the Cambrian across Belle Isle Strait.

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* *Bull. Mus. Comp. Zool., Geolog. Series*, vol. v, No. 5, 1902.

Overlying the slates and in visible contact with them, is a conformable bed of light gray lava varying from 0.9 meter to 1.2 meter in thickness. This is an aphanitic rock in which the microscope shows evidence of very thorough alteration. A colorless, isotropic base seems to represent original glass. Within it are small, triclinic, polysynthetically twinned feldspars which are rather vaguely crystallized, with a characteristic poor development of the twinning trace. No other original material appears in the thin section. Both glass and feldspar are largely replaced by secondary matter which may have been derived also from pyroxene or other bisilicate phenocrysts. No trace of the latter nor of an iron ore has been found. Both the feldspar and isotropic base are shot through with needles of colorless to pale green actinolite, and are also replaced by chlorite, yellow epidote, zoisite and most abundant calcite. The whole forms a good example of an almost completely altered lava which nevertheless remains tough and relatively hard. The very poor preservation of the feldspar prevents sure identification of the particular variety present but it is probably basic andesine or labradorite. The rock may have been of a type intermediate between tachylite and normal basalt; it is vesicular at both upper and lower contacts.

Immediately above the lava sheet is the pillow lava, proved to be about 60 meters in thickness, and, in its turn, the pillow-lava is overlain by black slates, a narrow band of which appears at the water's edge just inside the entrance to the harbor. (Fig. 2.)

All these comformable beds have shared in the general mountain-building processes that have affected northern Newfoundland. With unusual distinctness of the slates about the harbor display a discordance between stratification dip and cleavage dip. At the sea-chasm referred to the two structures seem to have a common strike of about N 25° E, a direction nearly parallel to the axis of Jacques Cartier Island and to the northwest shore of Kirpon Island. We have here, in fact, to do with almost the extreme northeasterly point which the "Appalachian trend" is known to reach. The dip of the cleavage is 70° to the ESE, corresponding to that of a system of rough, parallel joints in the pillow-lava. The dip of the bedding is but 50° in the same direction. Small dip-faults were seen in the sea-cliff. Greater dip-faults of considerable but unknown throw cut off the entire series along the axis of the "tickle" and again at a point about 370 meters to the southeast of the headland at the sea-chasm.

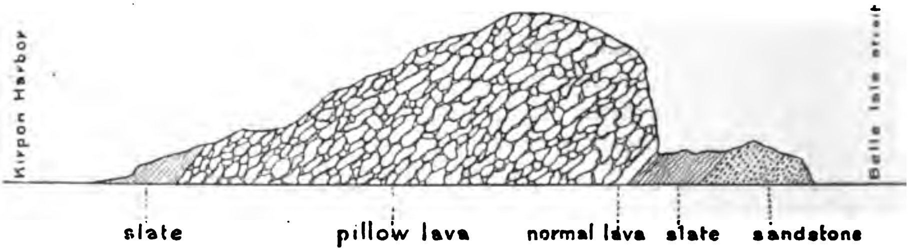

FIGURE 2.—Dip-section at northeastern end of Jacques Cartier Island, looking southwest. Horizontal scale, 130 feet to the inch; vertical scale, 100 feet to the inch. Size of pillow exaggerated.

Structure of the pillow-lava.—The pillow-lava, on account of its unusually good exposure and remarkable structures, occupied most of the short period of time which was granted for the investigation of these rocks. The accompanying illustrations, together with the accounts of pillow-lavas by Gregory, Ransome, Teall, Peach and Horne, and others, will render superfluous a complete verbal statement of the features characterizing the deposit. It is composed throughout of round, generally smooth, "bale-like," "pillow-form," commonly ellipsoidal masses of lava. (Plate XIV, Fig. 2.) These are discontinuous and perfectly individualized as a rule. They range from 5 cm. to 2 meters or more in greatest diameter. The interstices between them, including the conspicuous triangular spaces occurring where three or more pillows meet, are filled with coarsely crystallized calcite, quartz and dark, cherty masses. Those minerals thus form a sort of attenuated cement for the whole deposit. Calcite and quartz, chiefly the former, likewise fill joints and the extremely numerous cracks that appear in roughly radial arrangement within each bolster-like mass.

The radiating cracks were often seen to be widest and most numerous in the center of the pillow, recalling the central gaping fissures of many septaria. Such cracks are to be interpreted as due to contraction of the lava in passing from the molten to the solid state. The outer surfaces of the pillows occasionally show the "bread-crust" form, and generally the entire surface of each pillow and the crust forming the outer 2 cm. to 10 cm. of the mass are highly vesicular after the pattern of ordinary basalt flows. The corresponding amygdules are filled with calcite or, more rarely, with chlorite, chalcedony or quartz. The removal of this filling material gives the otherwise smooth surfaces of the pillows a pitted look. The pillows are also similar to those of California, Minnesota, Scotland, the Fichtelgebirge, etc., in showing plain evidence of their having been once sufficiently molten to yield somewhat to the action of gravity. The surfaces of contact are often sympathetic, an indentation of one nicely matching a protuberance from the pillow adjoining. Sometimes a large, overlying pillow will be seen to lie on a sort of pavement made up of a half-dozen or more smaller ones flattened on their upper sides parallel to the longer axis of the larger pillow. (Fig. 3.) The flattening of the larger pillows almost invariably causes them to

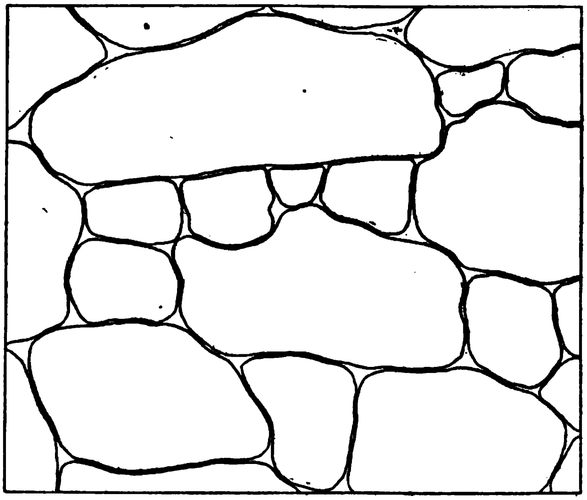

FIGURE 3.—Diagram of strike section in pillow-lava, Jacques Cartier Island. Scale 1 : 25.

lie concordant with the true dip of the slates alongside. In some cases the surfaces of single pillows, weathered out from their calcite matrix, were seen to have the exact appearance of ropy lava.

A microscopic feature that especially distinguishes this pillow-lava is found in the appearance of two distinct kinds of material, which, in addition to the amygdule fillings, composes each of the pillows. In most of the small ones the chief constituent is a dark, brownish-gray or greenish-gray, aphanitic, basaltic-looking rock substance continuous from center to circumference. Within it, numerous round, light-gray to light greenish-gray bodies from 2 to 15 millimeters in diameter, lie embedded. (Plate XV, Fig. 3.) These bodies are less rapidly destroyed by the weather than their matrix and hence usually project so as to give the rock a "pimply" appearance. There is always a sharp line of demarkation between the two kinds of material, indicating that the differentiation of the two dated from the time of original solidification. The lighter-colored included bodies are, in fact, believed to be varioles, though it will be seen that, in their present highly altered condition, some of the characteristics of true varioles are absent. There is a marked increase in the size and abundance of the varioles with increasing distance from the periphery of the pillow. In that phenomenon is to be traced a connection with the yet more abundant pillows in which the core of each is occupied by a continuous mass of the variole substance. (Plate XIV, Fig. 2.) This common feature of the Newfoundland rock does not seem to belong to the well-known variolitic pillow-basalt of Mont Genèvre, although, in other respects, there is a close resemblance between the two lavas. All transitions may be seen from the pillows of the first class to those where the variole substance composes as much as one-half to three-quarters of each pillow. The latter proportions adhere more especially to the large pillows. In no case was the variole substance apparent at the surface of the pillow. As at Mont Genèvre the varioles are generally arranged in concentric strings roughly parallel to the pillow-periphery. Near the light-gray core the varioles often anastomose and may form branching vermiform projections from the core into the dark-colored crust. While the isolated varioles are commonly spherical or nearly so, it was observed in several instances that they were flattened so as to lie parallel to the true dip, i.e. in the same sense as the pillows themselves.

Petrography.—The rock in the field is apparently fresh and it was expected, in view of the intense glaciation this region has suffered and because of the rapidity of wave-erosion at the sea-chasm, that extensive alteration of the lavas through weathering had not taken place. It was therefore hoped that the microscope would throw light on the origin of the peculiar differentiation of matter in the pillows. But every thin section studied showed that both varioles and matrix have suffered almost complete decomposition.

The aphanitic matrix is, in thin section, nearly colorless, with a pale green cast. It consists of a confused, structureless, massive mat of obscure feldspathic material, accompanied with exceedingly abundant calcite and with many ragged colorless tremolite or actinolite crystals, much chlorite, zoisite and abundant yellow grains of epidote. Very rarely one or two minute grains or idiomorphic crystals of magnetite will appear in a slide. Finally, numerous colorless, isotropic areas occur between these various minerals. Such areas may represent original glass, though some of it suggests opal and infiltrated chalcedonic silica. Maximum extinctions in the zone of symmetry of the feldspars showed values of about 17°, indicating andesine. The feldspar is often characterized by radial aggregation. With the magnetite and the rather doubtful glass, it represents the only original matter in the matrix.

The varioles seem to be even more completely made up of decomposition products. The most prominent constituent occurs in the form of long, frayed-out skeleton-crystals, shot through the generally ground-mass like phenocrysts in an igneous base. These crystals vary from 0.1 mm. to 1.0 mm. or more in length and from 0.02 to 0.25 mm. in width. They are generally bleached to a colorless condition with a corresponding feathering out into irregular needles of tremolitic habit, but, here and there, green and rather strongly pleochroic areas, with the characters of actinolite, merge into the colorless amphibole. It is believed that the skeleton-crystals represent highly altered actinolite crystals. On account of decomposition, they rarely show amphibole cleavage in sections transverse to the longer axes of the skeletons. Along with the bleaching of most of the little amphibole substance still remaining, there has occurred within the limits of the skeleton-crystals, the extensive generation of chlorite, zoisite, calcite, chalcedony, and abundant, single and aggregated, grains of yellow epidote. The skeleton-crystals sometimes, though rarely, show a tendency to aggregate in either of two ways. They form small radial groups irregularly placed at intervals in the variole, or a number of the individual crystals may in the section, lie roughly parallel to one another in a manner very similar to that of the small, colored pyroxenes forming "palisade-structure" in the varioles of the Annalong dike of Sollas.* The analogy between the Irish and Newfoundland varioles is so striking that one is tempted to regard the skeleton-crystals of the American rock as pseudomorphs after pyroxene. Basal sections have irregular octagonal outlines similar to those of phenocrystic augite. No trace of that mineral has been found, however, and one can go with certainty no further back in tracing the history of the skeletons than to the amphibole stage antedating the existing masses of secondary material.

The ground-mass in which the skeleton-crystals are embedded, is a confused mesh of minute, relatively long, needles of tremolite or bleached actinolite, matted together with abundant chlorite, chalcedonic silica, epidote, zoisite, quartz, and, apparently, minute apatites. With the exception of the last-mentioned mineral, of whose presence, indeed, the writer is not entirely certain, all this substance is plainly secondary. No trace of feldspar, or pyroxene and generally no iron-ore of any kind was to be discovered in the varioles. In one slide a couple of minute grains of magnetite probably represent primary material. There seems to be a relation between the size of the varioles and the length and thickness of the skeleton-crystals. The larger varioles so far as examined in thin section, contain the longest and broadest skeletons.

Chemical analyses have not been made, since they could throw but little light on the original nature of the variolite. The character of the decomposition products, the relation of the varioles to the matrix, to the aphanitic crust and to the periphery of each pillow, are so closely similar to the variolite of the Fichtelgebirge,[*] of Point Bonita,[†] of the Lleyn[‡] and of Mont Genèvre,[§] that there can be little doubt that the Newfoundland pillow-lava is a basalt or at least that it is no more acid than an augite andesite. Using Rosenbusch's designation for these special basaltic rocks, the Newfoundland lava may be called a greatly altered, variolitic spilite possessing the peculiar ellipsoidal or pillow structure.

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* *Proc. Roy. Dublin Soc.*, vol. vii, 1892, p. 516.

The strike and other field relations, except the angles of dip, as well as the petrography of the thick deposits seen on Kirpon Island and at Fortune Bay, (dip nearly vertical) are essentially identical with those just detailed for the rock on Jacques Cartier Island. It is, in fact, believed that, notwithstanding the fault at the entrance to Kirpon Harbor, that the outcrops on Jacques Cartier Island and Kirpon Island belong to the same deposit. In all three localities, the pillow-lava is more resistant to the weather than the associated slates and sandstones, and forms strong ridges in the topography.

The Origin of Variolite.—Much has been written concerning the causes underlying the development of varioles in basic rocks. It is clear that the Newfoundland occurrence cannot, on account of the all but complete decomposition of the rock, throw much additional light on this question. From the sharpness of the boundaries between variole and matrix and from the well defined difference of habit of the sets of secondary minerals composing the two elements of the rock, one must conclude that the varioles are, in date of formation, to be referred to the period of cooling of the lava from its once molten condition. The studies of the European variolites have indicated, too, the strong probability that in the development of the varioles, there is little, if any, chemical differentiation in the magma. Loewinson-Lessing suggests that the causes are probably external, as for example, rapid cooling *per se,* but concludes that the causes are really unknown.[‖] Cole and Gregory say: "The variolite of the Durance occurs *in situ* as a selvage on the surfaces of these diabases among themselves as blocks in the fragmental rocks, which are regarded by us as tuffs; and occasionally as a selvage to the diabase dikes. This product of rapid cooling was originally a spherulitic tachylite, and has become devitrified by slow secondary action. Variolite stands in the same relation to the basic lavas as pyromeride does to those of acid character."[*] Gregory concludes from his study of the Berneck variolite in the Fichtelgebirge, that, "though the varioles be the product of rapid cooling, too sudden a solidification of the diabase may prevent their formation. For a similar reason the amygdaloidal is less variolitic than the compact diabase, the loss of water that occupied the vesicles having diminished the fluidity of the rock."[†] A review of the literature dealing with variolite seems to show that it is best developed within "ellipsoidal" or pillow-lava, though a goodly number of instances are on record showing that the structure may appear just inside the glassy selvage of quickly cooled diabase dikes. In the paper of Cole and Gregory just quoted there will be found a full set of references to the previous investigations of variolite.[‡] In North America, two occurrences, both in pillow-lava, in addition to this one from Newfoundland, have since been described by Ransome[§] and Clements.[‖] In Europe several new localities have afforded examples of the rock. Cole has noted variolitic diabase in Anglesey[¶] and in County Down, Ireland;[°] Sollas, variolitic diabase in Wicklow County, Ireland;['] and Miss Raisin variolitic pillow basalt from the Lleyn, Wales.['']

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[*] J. W. Gregory. *Quart. Jour. Geol. Soc.*, vol. xlvii, 1891, p. 45.

[†] F. L. Ransome. *Bull. Dept. Geol. Univ. Calif.*, vol. i, 1898, p. 71.

[‡] Miss C. A. Raisin. *Quart. Jour. Geol. Soc.*, vol. xlix, 1893, p. 145.

[§] G. A. J. Cole and J. W. Gregory. *Ibid.*, vol. xlvi, 1890, p. 295.

[‖] *Tscher. Min. und Petrog. Mitth. Neue Folge*, vol. vi, 1885, p. 299.

The phenomena at all these localities seem to bear out the general conclusions of Cole and Gregory. Although there is but little direct microscopic or chemical evidence on the point, it seems justifiable to apply their explanation of the variolitic structure to the Newfoundland rock. The identity of decomposition products in variole and matrix certainly argues against any significant chemical differentiation in the magma at the time of variole-formation.

The Origin of the Pillow Structure.—In the latest important publication on pillow-lava, Clements has given a useful review and bibliography of the subject. He has considered the

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[*] *Quart. Jour. Geol. Soc. London*, vol. xlvi, 1890, p. 331.
[†] *Ibid.*, vol. xlvii, 1891, p. 61.
[‡] *Op. cit.*, p. 327.
[§] *Op. cit.*, p. 99.
[¶] *Monograph U. S. Geol. Surv.*, vol. xxxvi, 1899, p. 108.
[‖] *Proc. Roy. Dublin Soc.*, vol. vii, 1891, p. 112.
[°] *Ibid.*, 1892, p. 511.
['] *Ibid.*, vol. viii, 1893, p. 94.
[''] *Op. cit.*

Locality	Describer	Year of publication	Geological Date of Eruption	Immediately Associated Sediments	Author's Theory of Origin	Remarks
New Brunswick	Ells	1879	Lower Silurian	Graptolitic slates	Concretionary dolerite	
Mont Genèvre, France	Cole and Gregory	1890	Post-Carboniferous	None	Bombs and rolled out pahoehoe	Variolitic
Aci-Castello, Sicily	Platania	1891	Post-Pliocene (?)	Clays	Due to intrusion into submarine silt	Variolitic (?)
Berneck, Bavaria	Gregory	1891	Post-Devonian	Shale and slate	Due to contraction	Variolitic
Ely, Minnesota	Winchell	1892	Pre-Cambrian	Jasperoid iron-ore and silicious schists	Agglomeratic acccumulation	
The Lleyn, Wales	Raisin	1893	Probably early Palaeozoic	Argillite?	Due to contraction	Variolitic
Pt. Bonita, California	Ransome	1893	Cretaceous (San Francisco Sandstone)	Red jasper	Viscous pahoehoe	Sometimes variolitic
Mullion Id., Cornwall	Fox and Teall	1893 and 1894	Palaeozoic (Ordovician)	Radiolarian cherts	Submarine flows of lava, partly intrusive into bottom silt	
Angel Id., California	Ransome	1894	Jurassic or Cretaceous	Radiolarian cherts	Intrusive but near the surface	
Co. Tyrone, Ireland	Geikie	1897	Lower Silurian	Cherts, jaspers, mudstones	Intrusive into water or watery silt	
Cader Idris, Wales	Geikie	1897	Lower Silurian	Slate	Same	
Ayrshire and Forfarshire, Scotland	Geikie	1897	Lower Silurian	Radiolarian cherts and mudstones	Same	
Crystal Falls Dist., Michigan	Clements	1899	Pre-Cambrian	?	A form of terrestrial aa lava.	Sometimes variolitic

geographical distribution of the rock and also the divergent views concerning the genesis of the discrete pillow-structure.* As a supplement to his summary, the following table has been prepared, showing the already determined main facts and conclusions regarding the origin, geological age, associated sediments, and variolitism of the principal occurrences.

The later writers have taken contrasting views of origin, which, however, have this point in common, that the pillow-structure is to be connected with the presence of abundant moisture at the surfaces over which the flows occurred. Teall, Geikie and Platania credit the phenomenon to submarine eruption whereby the lava has flowed either directly into water or has been intruded into the water-soaked oozy silt of the sea-bottom. Ransome has stated his belief that the structure is not confined to surface-flows but may be found in dike-like masses intruded near the surface of a rock-series now represented by radiolarian cherts and by sandstones. 'Clements, on the other hand, compares the Michigan ellipsoidal basalt to the aa lava of Hawaii and Santorin and rejects Teall's hypothesis of a submarine origin. The following quotation is taken from the Crystal Falls monograph. "Both Ransome and Teall compare the ellipsoidal basalts with pahoehoe lava. The latter also suggests a submarine origin for the basalts studied by him. It should be noted that pahoehoe lava in its typical occurrence in Hawaii is found only in dry places, whereas the aa is confined to those parts of the lava stream—which in other parts of its course is perhaps developed as pahoehoe—where it crosses moist valleys or other depressions presumed to have contained a considerable amount of moisture.

"In the case of some of the block lava of Santorin described by Fouqué, with which this may be compared, the conditions were such that the lava practically welled up through the water.

"From Dana's description it appears that lava in the pahoehoe form can not exist in the presence of moisture, being changed to the aa form. It would thus seem that Teall's statement of a submarine origin for the pahoehoe lava is untenable."†

The grounds for Clements' rejection of the submarine hypothesis do not seem satisfactory to the present writer. The facts stated in the paragraphs quoted seem, on the contrary, to point to the correctness of Teall's position. Teall doubtless meant that the *detailed* surface of the lava-pillows is more like that assumed by pahoehoe than like the ragged surface of aa blocks, a fact which is fully corroborated in the Newfoundland occurrence. (See Plate XV, Fig. 4.) In other respects certainly well recognized by Teall, pillow-lava is closely allied to the aa form. The conspicuous absence of rugosites in the pillows produced from lava welling out and rolling up into ellipsoids may be inherent in the nature of submarine aa flows. At any rate, it is in the highest degree probable that a smooth, often ropy, surface is impressed on the lower blocks overridden by an aa lava-flow. The great bulk of the units in a pillow-deposit must be compared with such blocks moulded by the weight of heavy overriding blocks rather than with the extremely cracked and rough blocks at the surface of a terrestrial lava-flow. The already well recognized common association of pillow-lavas with radiolarian cherts and with other contemporaneous marine sediments occurring above and below, and within the interstices of, a pillow-deposit, forms a strong argument in favor of Teall's view. At all of the Newfoundland localities, the lava is overlain and underlain by conformable argillitic and arenaceous strata which are without doubt the result of sedimentation in fairly deep water. The deposition seems to have been discontinuous only by virtue of the short-lived, rapid out-flow of lava on the sea-floor. That the Newfoundland lava is not intrusive into loose bottom silts in this particular instance* is shown by the apparently complete absence of argillaceous material such as would be expected to become incorporated in the mass between and within the pillows as the latter would be rudely rolled and thrust through the silt. On that supposition, moreover, it would be difficult to explain the existence of the highly vesicular, continuous lava-flow underlying the whole pillow-deposit.

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* *Monograph xxxvi, U. S. Geol. Surv.*, 1899, p. 118.
† CLEMENTS. *Op. cit.*, p. 123.

Conclusion.—The writer has therefore concluded that, on the best working hypothesis, the Newfoundland rock is the product of the extrusion of basic lava into sea-water of some depth. That view is confirmed by Russell's recent discovery of pillow-lava formed where the Snake River basalt ran into lake-basins.* The structure of the Newfoundland deposit is that expected in the deeper parts of the Hawiian aa flows, or may possibly be affected by as yet unknown special conditions of submarine extrusion by which each pillow has assumed the details of the pahoehoe surface. With this conception of origin there agree; the evidence of quick cooling with the incidental variolitism; the extensive radial, concentric and irregular cracking each pillow has suffered; and the profound alteration of the lava due to the easy ingress of weathering agents along the thousands of microscopic and larger cracks opened up by the rapid chilling. Next to the possession of their peculiar structure, the pillow-lavas described in Europe and America have no more prominent and unvarying characteristic than this one of manifest, profound, metasomatic alteration of the rock.

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*Cf. experiment by JOHNSTON-LAVIS, South Italian Volcanoes, Naples. 1891, p. 42.

LEGENDS for *figures* and *plates*.

PLATE XIV. Fig. 1.—View of Kirpon Harbor, looking northeast. The two prominent ridges in the upper left-hand quadrant of the view, occurring, respectively, on Jacques Cartier Island and Kirpon Island, are underlain by pillow-lava.

Fig. 2.—Interior of one of the pillows, showing dark aphanitic crust, varioles, core of variolitic substance, and calcite matrix in which the pillow lies embedded.

PLATE XV. Fig. 3.—Variolite from the interior of a pillow. The scale is two inches long.

Fig. 4.—Natural surface of part of a small pillow removed from its calcite matrix, illustrating the smoothness of the pillows and the vesicular structure of the outer crust.

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* *Bull. U. S. Geol. Surv.*, No. 199, 1902, p. 113.

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THE CLASSIFICATION OF IGNEOUS INTRUSIVE BODIES

REGINALD A. DALY

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The author

THE CLASSIFICATION OF IGNEOUS INTRUSIVE BODIES[1]

REGINALD A. DALY
Ottawa, Canada

CONTENTS

THE NEED FOR A CLASSIFICATION.
FORMER CLASSIFICATIONS.
DEFINITION OF TERMS DESCRIPTIVE OF INTRUSIVE BODIES.
PRINCIPLES OF CLASSIFICATION.
PROPOSED CLASSIFICATION OF IGNEOUS INTRUSIVE BODIES.

THE NEED FOR A CLASSIFICATION

At the present time geological science is engaged with no general question more widely and thoroughly discussed than that of the origin of the igneous rocks. The elaborate chemical studies of those rocks, the many new classifications of rock species, the modern experiments in the synthesis of natural silicates, and the experiments on the physical and chemical properties of molten silicates, have as their chief end the demonstration of the facts upon which a stable theory of rock genesis can be founded.

All such studies must be pursued with constant reference to the actual occurrences of igneous rocks in nature. Petrology is dependent upon, knit together with, field geology; the heart of geological philosophy is petrology in its broad sense. On the chemical side the laboratory observations of rock-analysts have been rated as "superior" (excellent, fair, or good) or as "inferior" (poor or bad). Similarly, field observations can be rated as superior or inferior according to the fulness and accuracy with which they supply the data from outdoor nature. Of those facts none is of more importance to petrology than the mode of occurrence of igneous rocks.

The field information required for the great group of the igneous intrusives relates to their shapes, sizes, and methods of intrusion. The statement of field facts depends on the precision of the terms used to describe them. That precision depends on definition. Scientific definition necessarily means classification.

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[1] Published by permission of the Canadian Commissioner, International Boundary Surveys.

Neither in the definition nor in the classification of igneous intrusive bodies is there at present unanimity or consistency among geologists. The same author defines "dike" or "sheet" or "batholith" in quite different ways on different pages. Of late years "laccolith," "boss," "stock," and practically every other term referring to igneous intrusions, have from different writers respectively received definitions varying in essentials. In several cases the difference of usage has sprung from the subjective influence of theories of intrusion. Some of the most recent definitions of older terms have thus become too intensive in meaning to fill the needs of the great body of field workers who are still in the wholesome attitude of mind that forbids the final adoption of any theory of intrusion for many important igneous bodies.

The writer believes that a comparatively full classification of igneous intrusive bodies is needed. The general adoption of a consistent, well-defined scheme of types—a scheme as complete as possible, but elastic enough to permit of new types—would tend to make field descriptions more scientific than many of them are at present. Such general adoption would mean a gain in precision, the soul of scientific writing; a gain in the ease with which a paper descriptive of igneous intrusions would be understood; and an economy of words induced by the employment of terms of definite, precise meaning. The filling-out of the scheme of classification to an extent quite beyond that now prevailing in standard text-books of geology should further have the effect of sharpening the eyes of the field observer. He may perhaps not be content to describe a given granite intrusion as simply a "mass," or an "area," or an "outcrop," if it be possible by the study of its contents to indicate the real form and relations of the granite body. The use of the term "mass" in that sense is often excellent because of the apparent impossibility of determining the true shape of the granite body; but such justifiable employment of the term implies that that particular body cannot as yet be thoroughly classified. A rather negative name has in such a case a distinct value. Of yet greater value is the positive reference of intrusive bodies to definite categories. A good observer always feels the pressure of the category. If his classification be systematic, his observing power is quickened, his report enriched; if his classification be that in general use, his descriptions will be of the greater service to the science.

The purpose of this paper is to present certain of the current definitions and classifications of intrusive bodies; from the definitions and classifications to attempt the deduction of the various principles underlying them; and, finally, to offer for discussion a classification which shall aim at a systematic and consistent use of the principles which seem best adapted to the case. As far as possible, these principles are the same as those already in common use among leading geologists.

FORMER CLASSIFICATIONS

A few representative classifications of igneous intrusive bodies will serve to show the range of types recognized by recent authors.

I. Sir Archibald Geikie, *Text-book of Geology* (4th ed., 1903), Vol. II, p. 722:
  1. Bosses (stocks).
  2. Sills, intrusive sheets.
     Variety: laccolith.
  3. Veins and dykes.
     Varieties: contemporaneous veins, segregation veins, multiple dykes, compound dykes.
  4. Necks

II. T. C. Chamberlin and R. D. Salisbury, *Geology* (1904), Vol. I., pp. 476, 477:
  1. Dikes.
  2. Necks or plugs.
  3. Sills.
  4. Laccoliths.
  5. Bysmaliths.
  6. Bathyliths.

III. F. Zirkel, *Lehrbuch der Petrographie* (1893), Vol. I, p. 539:
  1. Gänge.
  2. Lagergänge.
  3. Gangstöcke.
  4. Apophysen.
  5. Stöcke.
  6. Intrusivlager.
  7. Lakkolithen.

DEFINITION OF TERMS DESCRIPTIVE OF INTRUSIVE BODIES

Dike.—The best established of all the terms used in the foregoing lists is "dike;" yet the variation in even recent definitions of it is apparent in such examples as the following:

I. G. K. Gilbert:[1]

> Dikes differ from sheets in that they intersect the sedimentary strata at greater or less angles, occupying fissures produced by the rupture of the strata.

II. G. P. Merrill:[2]

> A dike: "an eruptive mass of varying width included between well-defined walls, and occupying a fissure or fault in previously consolidated rocks. Such are inclined at all angles with the horizon, and are usually of very moderate width, but may extend for miles."

III. T. A. Jaggar:[3]

> A dike is an elongate intrusive igneous body occupying a fissure in any sort of rock, the walls of which at the time of intrusion were vertical or, if inclined, at angles nearer the vertical than the horizontal. A dike must have longitudinal extension much greater than its breadth, but may vary in thickness from an inch to several hundred feet. A dike may be irregular or may follow a sinuous course; it may be intruded between the beds of vertical or steeply inclined sediments; it frequently follows joint surfaces and has smooth and plane bounding walls. It must be noted that a flat igneous mass intruded between horizontal or nearly horizontal strata, and subsequently upturned with them to a vertical position, is not a dike, but a sill.

IV. Sir Archibald Geikie:[4]

> Dykes are veins of eruptive rock, filling vertical or highly inclined fissures, and are so named on account of their resemblance to walls (Scotice, dykes).

V. T. C. Chamberlin and R. D. Salisbury:[5]

> When lava is forced into crevices or rises to the surface through fissures, and the residual portion solidifies in them, it gives rise to dikes.

All the foregoing definitions agree in ascribing to a dike the characteristic form of a fissure-filling. Gilbert, in the quotation; Geikie, and Chamberlin and Salisbury, in their respective contexts, expressly exclude from the category of dikes all sheetlike intrusions thrust into the bedding-planes of stratified formations, whatever is or has been the angle of dip. The same usage appears in the writings of most field geologists, whether English-speaking or not. Geikie emphasizes the generality (necessity?) of high angles of dip in true dikes. Jaggar makes the angle of dip at the time of intrusion the principal criterion in distinguishing dikes from sills, and advocates a definition of both dike and sill which is not followed by the great majority of geologists. J. D. Dana[1] states that dikes may vary "in position from vertical to horizontal," and it is seen that Gilbert's and Merrill's definitions agree with that usage of the term. Since most dikes are nearly or quite vertical, the difficulty of classifying those eruptive fissure-fillings which lie nearer horizontal than vertical planes has not often been mentioned in geological literature.

---

[1] *Geology of the Henry Mountains* (1877), p. 20.

[2] *Rocks, Rock Weathering and Soils* (1897), p. 50.

[3] *Twenty-first Annual Report of the U. S. Geological Survey*, Part 3 (1901), p. 172.

[4] *Text-book of Geology* (4th ed., 1903), Vol. II, p. 743

[5] *Geology* (1904), Vol. I, p. 476.

Most geologists are thus agreed that dikes in stratified formations are bodies always cross-cutting the bedding planes. Many geologists agree that the angle of dip is immaterial. All agree as to the criterion of form, namely, that of a fissure-filling narrow in proportion to its length and bounded by parallel or nearly parallel walls of country rock.

According to the commonest and best usage, an igneous dike (*a*) is an injected body, (*b*) has nearly or quite parallel walls, (*c*) is narrow in proportion to its outcropping edge, (*d*) cuts across the bedding when the invaded formation is stratified, and (*e*) has any angle of dip.

When stratification and cleavage or schistosity are not coincident, such an intrusive body is generally called a dike, even though it follows the planes of cleavage or schistosity. This usage will be adopted in the classification proposed in this paper.

Multiple dikes are compound intrusions of dike form, due to successive injections of homogeneous material on the same fissure.[2] For illustrations, see Harker, *Tertiary Igneous Rocks of Skye*, pp. 296–304; A. Geikie, *Ancient Volcanoes*, Vol. II, p. 417.

Composite dikes are compound intrusions of dike form, due to successive injections of different materials into the same fissure.[3]

---

[1] *Manual of Geology*, 4th ed., 1895, p. 298.

[2] Geikie, *Text-book of Geology*, Vol. II, p. 746.

[3] J. W. Judd, *Quarterly Journal of the Geological Society*, London, Vol. XLIX (1893), p. 536; A. Harker, *Tertiary Igneous Rocks of Skye* ("Memoirs of the Geological Survey of Great Britain," 1904), p. 197.

A. Geikie has used "compound" in the sense of "composite" in the foregoing definition;[1] Lawson has used "multiple" with the same meaning. The nomenclature given in the above definitions is preferred, as it brings out the analogy with "multiple" and "composite" sills and laccoliths—types already well named and established.

A composite dike is illustrated in Fig. 1.

A *dike network* is a reticulate group of dikes simultaneously injected. For illustration see *Bulletin No. 209*, U. S. Geological Survey, 1903, section, Plate 7.

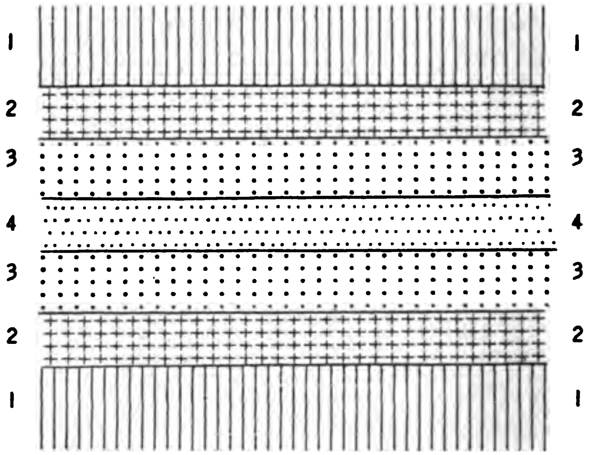

FIG. 1

Intrusive vein.

I. J. B. Jukes:[2]

> When the injected mass has arisen along an opened fissure, and solidified there as a wall-like intrusion, it is called a *dyke*. When its path has been less regularly defined, and penetrates the surrounding rocks in a wavy thread-like fashion, this irregular protrusion is called a *vein*.

II. A. Geikie:[3]

> *Veins* have been injected into irregular branching cracks.

---

[1] *Text-book*, Vol. II, p. 746.

[2] *Manual of Geology*, edited by A. Geikie (1872), p. 263.

[3] *Text-book* (1903), p. 744.

Contemporaneous vein.

Forms part of the igneous rock in which it occurs, but belongs to a later period of consolidation than the portion into which it has been injected.[1]

Apophyses or tongues are dikes or veins which, either directly or by inference from field relations, can be traced to larger intrusive bodies as the source of magmatic supply for dike or vein.[2]

Intrusive sheet.—This familiar expression has generally been defined as equivalent in meaning to "sill."[3] It may well be extended to cover the case of an igneous layer injected on a plane of unconformity in stratified formations, when the igneous layer is thus sensibly parallel to the bedding-planes of one of the stratified formations. This type, for lack of a better term, may be called an *interformational sheet.* For illustration of such a sheet on a colossal scale, see "Map of Northern Nickel Range," Sudbury District, Ontario, by A. P. Coleman.[4]

Sill.

I. A. Geikie:[5]

A *sill* is a sheet of igneous material which has been injected into a sedimentary series and has solidified there, so as to appear more or less regularly intercalated between the strata.[6]

II. T. A. Jaggar.[7]

A sill is an intrusive sheet forced between strata which are horizontal or which, if tilted, lie at angles more nearly horizontal than vertical. . . . . Transitions between dike and sill occur when a sill breaks upward at an angle of 45°, or when a dike follows the bedding-planes of strata inclined at that angle.

III. Chamberlin and Salisbury:[8]

If the lava is forced between beds of rock in the form of a sheet, and solidifies there, it is called a *sill.*

The definition of I and III is that which is adopted by nearly all authors writing in English on this type of intrusive body. The term "sill" has also its equivalents in this sense in other languages. Definition II is not only contrary to general usage but suffers from special imperfections due to the artificial nature of the chief criterion distinguishing dike and sill. (Compare Definition III of "dike.") Among those imperfections is the difficulty of classifying by Definition II many intercalated sheets now dipping at high angles, for with them it may be impossible to say what were their original dips.

---

[1] Geikie, *op. cit.*, p. 738.

[2] See A. Geikie, *Quarterly Journal of the Geological Society*, Vol. L (1894), p. 222, and *Ancient Volcanoes of Great Britain*, Vol. II (1897), p. 439.

[3] E. g., Jukes, *Manual*, p. 254; Gilbert, *op. cit.*, p. 20; Iddings, *Twelfth Annual Report of the U. S. Geological Survey*, Part 1, p. 578; Geikie, *Text-book*, p. 732.

[4] *Report of the Bureau of Mines*, Ontario, 1904.

[5] *Geology of Eastern Fife* ("Memoirs of the Geological Survey of Scotland," 1902), p. 189.

[6] Cf Geikie, *Text-book*, p. 732. [7] *Op. cit.*, p. 172. [8] *Op. cit.*, p. 476.

It thus seems best to adhere to the prevailing use of the term "sill" in a systematic classification of intrusive bodies. A sill may be of great thickness, as illustrated on Fig. 2, but it is necessary that the sheet shall hold its thickness for considerable distances along its outcropping edge.

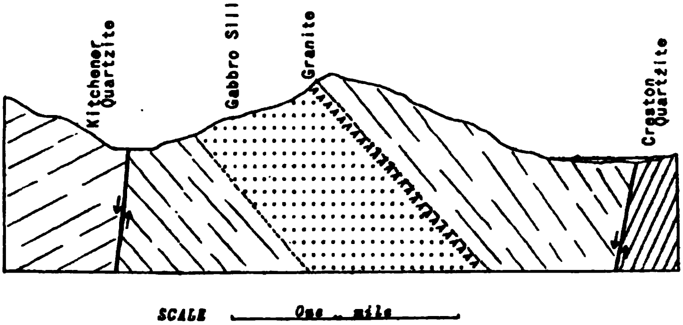

FIG. 2

A *multiple sill* is a compound intrusion of sill form and relations, and is the result of successive injections of one kind of magma along a bedding-plane in a stratified formation.[1] For a remarkable illustration, see Harker.[2]

A *composite sill* is a compound intrusion of sill form and relations, and is the result of successive injections of more than one kind of magma along a bedding-plane in a stratified formation.[3]

A section of a composite sill is illustrated in Fig. 3.

---

[1] See A. Geikie, *Ancient Volcanoes of Great Britain*, Vol. II, pp. 318 ff.; and especially A. Harker, *op. cit.*, p. 197.

[2] *Op. cit.*, p. 239.

[3] See Harker and Geikie, same pages as noted for multiple sills.

Laccolith.—Divergence of definition and usage becomes very marked in the case of the term "laccolith."

I. The original definition by G. K. Gilbert:

> The station of the laccolite being decided, the first step in its formation is the intrusion along a parting of strata, of a thin sheet of lava, which spreads until it has an area adequate, on the principle of the hydrostatic press, to the deformation of the covering strata. The spreading sheet always extends itself in the direction of least resistance, and, if the resistances are equal on all sides, takes a circular form. So soon as the lava can uparch the strata, it does so, and the sheet becomes a laccolite. With the continued addition of lava, the laccolite grows in height and width, until finally the supply of material or the propelling force so far diminishes that the lava clogs by congelation in its conduit and the inflow stops.[1]

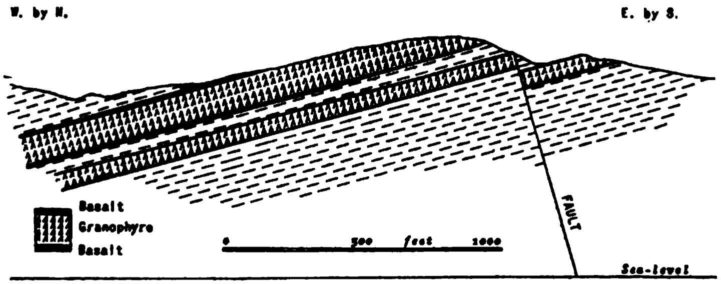

FIG. 3

> As a rule, laccolites are compact in form. The base, which in eleven localities was seen in section, was found flat, except where it copied the curvature of some inferior arch. Wherever the ground plan could be observed, it was found to be a short oval, the ratio of the two diameters not exceeding that of three to two. Where the profile could be observed, it was usually found to be a simple curve, convex upward, but in a few cases, and especially in that of the Marvine laccolite, the upper surface undulates. The height is never more than one-third of the width, but is frequently much less, and the average ratio of all the measurements I am able to combine is one to seven.
>
> The ground plan approximates a circle, and the type form is probably a solid of revolution—such as the half of an oblate spheroid.[2]
>
> The laccolite is a greatly thickened sheet [sill] and the sheet [sill] is a broad, thin, attenuated laccolite.[3]
>
> The laccolite in its formation is constantly solving a problem of "least force," and its form is a result. . . . . A laccolite grows "by lifting its cover."[4]

The clearness and precision of Gilbert's description gives a distinct and unmistakable individuality to his original type. It is a greatly thickened sill of compact, domical form, with (*a*) a limital thickness, (*b*) a limital area, (*c*) a flat base, (*d*) an oval or circular ground plan, and (*e*) a specialized method of intrusion, namely, by lifting a stratified cover which thus assumes a dome structure.

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[1] *Op. cit.* (1877), p. 95. [2] *Ibid.*, p. 55. [3] *Ibid.*, p. 20. [4] *Ibid.*, p. 91.

Gilbert notes, as a first variation on the simple type, a compound type of laccolith which is "built up of distinct layers. . . . . It is probable that all the larger laccolites are composite, having been built up by the accession of a number of distinct intrusions."[1]

He continues:

> If the strata had experienced anterior displacements so as to be inclined, folded, and faulted, a symmetrical growth of laccolites would have been impossible, and the mountains would not have yielded a knowledge of the type form. But the type form being known, it is to be anticipated that in disturbed regions aberrant forms will be recognized and referred to the type.[2]

II. Cross[3] illustrates many examples of true laccoliths which show aberrant forms in just such a way as was foretold by Gilbert. Cross still holds that the body is a laccolith even if its expansion has taken place from a plane only approximately parallel to the bedding of the invaded strata. He emphasizes the asymmetric dome as more nearly the real shape of a laccolith in nature, and attributes such irregularity of form chiefly to lines of weakness existing in the sedimentary formation before intrusion took place. A more fundamental difference between the definitions of Gilbert and Cross appears in their respective statements as to the method of intrusion. Cross holds that the deformation of the stratified cover is in many cases not simply due to the force of a gigantic hydrostatic press; that the deformation was then incidental to the gaping of strata undergoing lateral, orogenic pressure, the magma being more or less passive as it was injected.

III. Weed and Pirsson[4] agree with the views of Cross, but Pirsson returns to the idea of the hydrostatic press as explanatory of the intrusions in the Judith Mountains. Both authors consider that a horizontal base is not necessary for a true laccolith, and that some laccoliths are doubly convex.

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[1] *Op. cit.*, p. 55.

[2] *Ibid.*, p. 98.

[3] *Fourteenth Annual Report*, U. S. Geological Survey, Part 2 (1894), pp. 184 ff.

[4] *Eighteenth Annual Report*, U. S. Geological Survey, Part 3 (1898), p. 581.

IV. Jaggar[1] found that the laccoliths of the Black Hills illustrated conclusions essentially equivalent to those of Cross, states his belief that the magmas were mostly passive during intrusion, the laccolith chambers being opened by orogenic stresses, and remarks that laccoliths may be doubly convex.

V. The recent definition of Chamberlin and Salisbury[2] returns once more to the original type of Gilbert: "If, after rising to a certain point in the strata, the lava arches the beds above into a dome, and forms a great lens-like or cistern-like mass, it constitutes a *laccolith.*"

It is seen that there is considerable diversity of usage for the term "laccolith." On the whole, this diversity is a sign of progress in geological science. Gilbert's ideal type has been supplemented by others that vary from the ideal in one or more particulars, under conditions which Gilbert himself foretold, if it were but in brief expression.

Those who have made actual researches among laccoliths, and have preserved the term "laccolith" with the original meaning of Gilbert's broader definition, are agreed on the following characteristics: (*a*) Whatever the origin of the force involved, a laccolith is always *injected.* (*b*) A laccolith is always in sill-relation to the invaded, stratified, formation; that is, the injection has, in the main, followed a bedding-plane; but, like sills, laccoliths often locally break across the bedding. (*c*) A laccolith has the shape of a plano-convex or doubly-convex lens flattened in the plane of bedding of the invaded formation. The lens may be symmetric or asymmetric in profile, circular, oval, or irregular in ground plan. (*d*) There are all transitions between sills and laccoliths.

For many illustrations of simple symmetric and asymmetric laccoliths, see the cited writings of Gilbert, Cross, Weed and Pirsson, and Jaggar.

Compound laccolith.—In the Judith Mountain type, as in the larger examples of laccoliths in the Henry Mountains, the whole intrusive body is divided by strong beds of the invaded formation. This gives the appearance of a number of distinct intrusions, one of them dominating, the others subsidiary, in size, but all of them composed of the same kind of material. If the magma has all been intruded at practically the same time, we have the "compound laccolith" of Weed and Pirsson.[1]

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[1] *Op. cit.*, p. 173.

[2] *Geology*, Vol. I, p. 476.

A *multiple laccolith* may be conceived, the name being formed on the analogy of "multiple dike" and "multiple sill." It would differ from a compound laccolith only in the fact that the deformation of the strata, while again similar in character to that produced during the intrusion of a simple laccolith, has been due to distinctly successive injections of the same kind of magma. This case has not yet been described as actually occurring in nature.

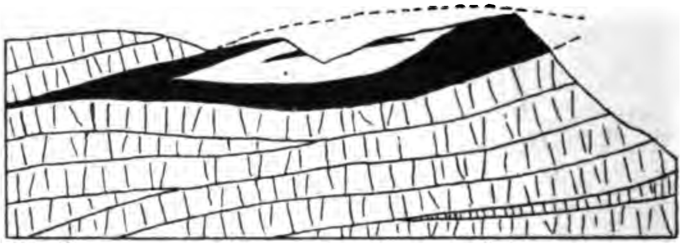

FIG. 4

Composite laccolith.—Harker[2] has noted the occurrence of "composite laccoliths" in the island of Skye. The analogy with composite dike and sill is again perfect. The principal distinction from both compound and multiple laccoliths is found in the heterogeneous nature of the magma successively injected in this last case. (See Fig. 4.)

Interformational laccolith.—Weed and Pirsson[3] have described as a laccolith a great, lenticular mass of porphyry injected along a surface of unconformity, namely, that between pre-Cambrian crystalline schists and a sedimentary Cambrian formation. Such a type is again aberrant from Gilbert's types, but should certainly be classed among the laccoliths; the writer proposes the not altogether satisfactory name "interformational laccolith" for this case. (See Fig. 5, and compare a similar section of an occurrence in the Black Hills of South Dakota, published in the *Annals of the New York Academy of Sciences*, Vol. XII (1899), p. 212.)

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[1] *Op. cit.*, p. 580; see figure.

[2] *Op. cit.*, p. 209.

[3] *Journal of Geology*, Vol. IV (1896), p. 402.

Plug.—Russell has described as "plutonic plugs" certain intrusions occurring in the Black Hills of Dakota. They "are composed of igneous matter forced into sedimentary strata and have a plug-like form."[1] He continues: "How the stratified beds below the domes that covered the plugs were displaced, or perhaps fused, so as to furnish room for the passage of the intruded material, is not clear." Again: "None of the plutonic plugs examined by me are associated with dikes or faults."[2] "They occur in a region where the stratified rock into which they were forced are essentially horizontal."[3]

Since neither the form nor the method of intrusion is clearly indicated, it is difficult to classify "plugs" in Russell's sense. It is to be noted that Jaggar[4] and Iddings[5] interpret some of Russell's original types as true laccoliths. Russell's statement does not make clear the distinction between "plugs" and stocks. The name "plug" has been rather commonly used as alternative with the magmatic filling of a volcanic vent.[6] For these various reasons, "plugs" will not be included in the proposed classification of this paper.

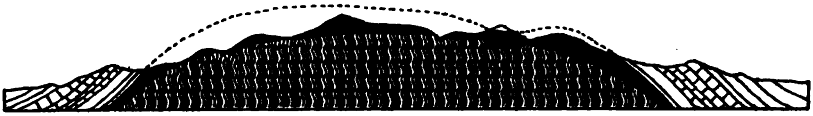

FIG. 5

Bysmaliths.—Allied to "plugs" in Russell's sense is the "bysmalith" of Iddings, described as an injected body filling a "more or less circular cone or cylinder of strata, having the form of a plug, which might be driven out at the surface of the earth, or might terminate in a dome of strata resembling the dome over a laccolith."[7] The downward termination of the original type bysmalith (Mt. Holmes) is found in a hypothetical Archean floor on which the porphyry of the bysmalith rests. See illustrations.[8]

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[1] *Journal of Geology*, Vol. IV (1896), p. 25.

[2] *Ibid.*, p. 42.

[3] *Ibid.*, p. 183.

[4] *Op. cit.*, p. 287.

[5] *Journal of Geology*, Vol. VI (1898), p. 706.

[6] Recently by Merrill, *op. cit.*, p. 51, and by Chamberlin and Salisbury, *op. cit.*, p. 476.

[7] *Monograph No. 32*, Part 2, U. S. Geological Survey (1899), p. 16.

[8] Iddings, *op. cit.*, p. 16; and *Journal of Geology*, Vol. VI (1898), p. 708.

Volcanic neck.—The solid-lava filling of a volcanic vent is evidently intrusive with reference to the formations traversed by the lava, whether those formations are composed of non-volcanic rocks or of agglomerate or tuff which has been pierced by thoroughly molten lava on its way to the surface. (See Fig. 6.)

"*Chonolith.*"—There remains for distinction a class of injected igneous bodies which are not included in any of the above-mentioned categories. In the dislocation of rock formations such as is brought about during mountain-building, actual or potential cavities are formed within the earth's crust. These are commonly filled with igneous magma squeezed into the individual cavity from below, from the side, or, it may be, from above. Dikes, sills, and bodies of laccolithic form (though not strictly of the laccolithic mode of intrusion, as designated by Gilbert) may thus originate. Yet very often the shape of the intruded mass is so irregular, and its relations to the invaded formations so complicated, that the body cannot be classified in any of the divisions so far named. Again, irregular injected bodies of a similarly indefinite variety or form are due to the active crowding-aside and mashing of the country-rock which is forced asunder by the magma under pressure. Or, thirdly, such bodies may be due to a combination of the two primary causes—orogenic stress opening cavities, and hydrostatic or other pressure emanating from the magma itself and widening the cavities.

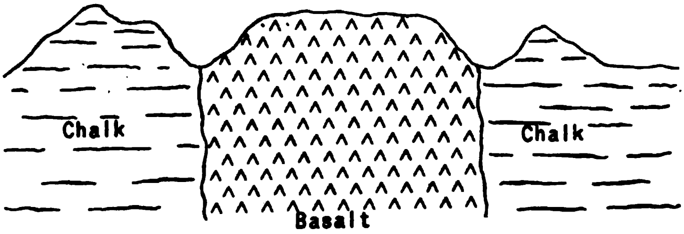

FIG. 6

The number and total volume of these irregular intrusions doubtless greatly exceed the number and volume of all the true laccoliths of the world. In the average mountain range the geologist is more likely to encounter injected bodies of the former kind than he is to discover true laccoliths.

No generally accepted name has yet been proposed for such irregular intrusions. "Laccolith" cannot be used, since that term denotes a definite form, and also implies a special mode of intrusion different from that here conceived. The writer has not been able to find a simple English word for the purpose, and suggests a name formed from the Greek on the analogy of "laccolith," "bysmalith," and "batholith." It is "chonolith," derived from χῶνος, a mold used in the casting of metal, and λίθος a stone. The magma of a "chonolith" fills its chamber after the manner of a metal casting filling the mold. Like a casting, the "chonolith" may have any shape.

A "chonolith" may be thus defined: "an igneous body (*a*) *in*jected into dislocated rock of any kind, stratified or not;[1] (*b*) of shape and relations irregular in the sense that they are not those of a true dike, vein, sheet, laccolith, bysmalith, or neck; and (*c*) composed of magma either passively squeezed into a subterranean orogenic chamber or actively forcing apart the country-rocks.

The chamber of a "chonolith" may be enlarged to a subordinate degree by contact fusion on the walls, or by magmatic "stoping."

An example of a "chonolith" is illustrated in Fig. 7.

Many intrusive bodies that have been mapped and illustrated with sections seem to belong to this same category. Among these may be mentioned a few taken from works dealing with the western Cordillera of the United States.

In the Little Belt Mountains folio of the U. S. Geological Survey, several "stocks" of granite, diorite, etc., are sectioned with relatively narrow feeding channels from below. The Three Forks (Montana) folio contains a map and section of a "laccolith" in non-laccolithic relations. Section "M–M" of the Ten Mile District Special folio shows a mass of granite injected after the manner of a "chonolith." South of Mount Stuart, Washington, the Mount Stuart folio illustrates an irregular intrusion of peridotite with "chonolithic" relations.

Cross[2] states that the intrusive body of Mount Carbon, Colorado, is injected and irregularly cross-cutting; it is not a true laccolith, but appears to be best placed in such a class as that here proposed.

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[1] The term "injected" is used here and elsewhere in this paper in a sense defined in the third paragraph of the following section on the principles of classification.

[2] *Op. cit.*, p. 191.

Weed and Pirsson[1] describe Judith Peak, Montana, as underlain by a "stock" of porphyry. Their section of the "stock" shows, however, a rapid constriction of the body as the section is followed downward. As will be noted on a following page, the section of a true stock typically enlarges downward so that such a body is "subjacent" rather than "injected" with respect to the invaded formations. On the supposition that the section of Weed and Pirsson correctly represents the actual underground relations, the Judith Mountain body has its nearest relatives among "chonoliths" and not among "stocks."

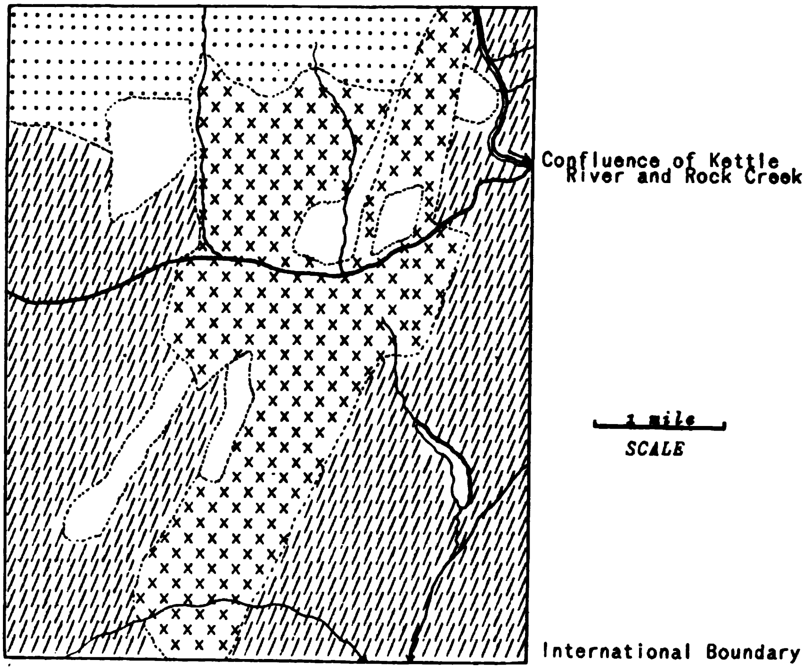

FIG. 7

Jaggar[2] describes the intrusive bodies of Dome Mountain and Whitewood Canyon in the Black Hills as injected bodies of marked irregularity both in shape and in relations to their respective country-rock formations. These bodies seem to be transitional between true laccoliths and typical "chonoliths," but belong to the latter class rather than to the former. Jaggar also describes the "False Bottom Stock" of phonolite in such terms as to lead one to suspect that it may be another, perhaps typical, body of the "chonolith" class.[1]

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[1] *Eighteenth Annual Report*, U. S. Geological Survey, Part 3, 1898, p. 533.

[2] *Op. cit.*, Plates 20 and 21, and pp. 209 and 217.

Jaggar,[2] collaborating with Howe, has experimentally reproduced the conditions under which some "chonoliths" have originated; namely, such bodies as have been injected primarily through the application of force resident in fluid magma under pressure (hydrostatic force). No attempt was made, in their valuable experiments, to imitate injection concomitant with regional deformation.

Whatever may be the validity of any or all of these several cases as illustrations of "chonoliths," there is no question that they can be called "stocks" or "laccoliths," or by any other of the established names, only at the sacrifice of much of the strength, precision, and usefulness of those names. On the other hand, there are thousands of irregular injected bodies which cannot properly be described by the use of any of the established names. It is to be noted, finally, that some such term as "chonolith" may be useful in suggesting the probable nature of an intrusive body in the case where its whole form is not certainly known. The context should then, of course, indicate that the author using the term has in mind only a probability and is making, as it were, simply a report of progress in the description of that particular body.

Boss.—A Geikie[3] defines bosses as

> masses of intrusive rock which form at the surface rounded, craggy, or variously shaped eminences, having a circular, elliptical or irregular ground plan, and descending into the earth with vertical or steeply inclined sides. Sometimes they are seen to have pushed the surrounding rocks aside. In other places they seem to occupy the place of these rocks through which, as it were, an opening has been punched for the reception of the intrusive material. . . . . In true bosses, unlike sills or laccolites, we do not get to any bottom on which the eruptive material rests.

He makes "stock" and "boss" synonymous.

In his *Text-book*[4] Geikie says: "Bosses (stocks) are amorphous masses that have disrupted the rocks through which they rise."[5]

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[1] *Ibid.*, p. 227.

[2] *Ibid.*, p. 302, and Plate 43, section 2.

[3] *Ancient Volcanoes*, Vol. I (1897), p. 88.

[4] Vol. II (1903), p. 722.

[5] Cf. also A. Geikie, *Geology of Eastern Fife* (1902), p. 189.

In English- and German-speaking countries "boss" and "stock" are almost invariably regarded as synonymous, but the latter term has much the greater vogue.[1] The general connotation of the word "boss" seems to warrant the restriction of its meaning so as to include only those stocks which have circular or subcircular ground plans on the surface of exposure. The word has been used to denote intrusions of the sort up to all diameters from a few hundred feet to several miles.

Bosses are "simple" when composed of material intruded in but one period; they are "multiple" or "composite" when composed of material intruded at two or more distinct periods of irruption. The distinction between the latter types is the same as between "multiple" and "composite" stocks.

An illustration of a simple boss is given in Fig. 8.

Stock.—Prevailing usage has fixed the meaning of "stock" as essentially equivalent to Geikie's definition of "boss." A stock is an intrusive body, but is not as clearly *in*jected as is the case with a dike, sill, or laccolith. A stock more or less conspicuously cuts across the structures of the invaded formations; its contacts are, in general, either vertical or highly inclined; its shape is irregular and not determined by planes of bedding or other structures in the country-rocks. It has no visible floor. Van Hise regards a stock as characteristically smaller than a boss,[2] but the present writer has found that general usage does not support that distinction.

Simple stocks are composed of material intruded in one period of irruption.

A *multiple stock* is composed of material demonstrably intruded in two or more periods of irruption, the material having been derived from the same kind of magma.

A *composite stock* is composed of materials demonstrably intruded in two or more periods of irruption, the materials having been originally derived from two or more kinds of magma. (Fig. 8.)

Magmatic differentiation or other influences may render heterogeneous the material composing a simple stock, or each member of either a multiple or a composite stock.

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[1] Cf. Zirkel, *Lehrbuch der Petrographie* (1893), Vol. I, p. 539.

[2] *Monograph No. 47*, U. S. Geological Survey (1904), p. 711.

Batholith.—Suess[1] has finally stated the definition of "batholith" in terms of a theory of intrusion which is at present in discussion. His definition may be freely translated thus: "A batholith is a stock-shaped or shield-shaped mass intruded as the result of fusion of older formations (orig. *Durchschmelzungsmasse*). On the removal of its rock-cover and on continued denudation, this mass either holds its diameter or grows broader to unknown depths (orig. *bis in die ewige Teufe*).[2] The name was invented to describe those largest of all intrusions, generally granitic, which are characteristically found in great mountain ranges; including, thus, "central granites," "intrusive mountain-cores," "Fussgranit," etc. The name has since been commonly used for bodies of intrusive rock with the general characteristics of stocks, but of much larger size than is generally attributed to stocks or bosses. This latter use is, moreover, rarely

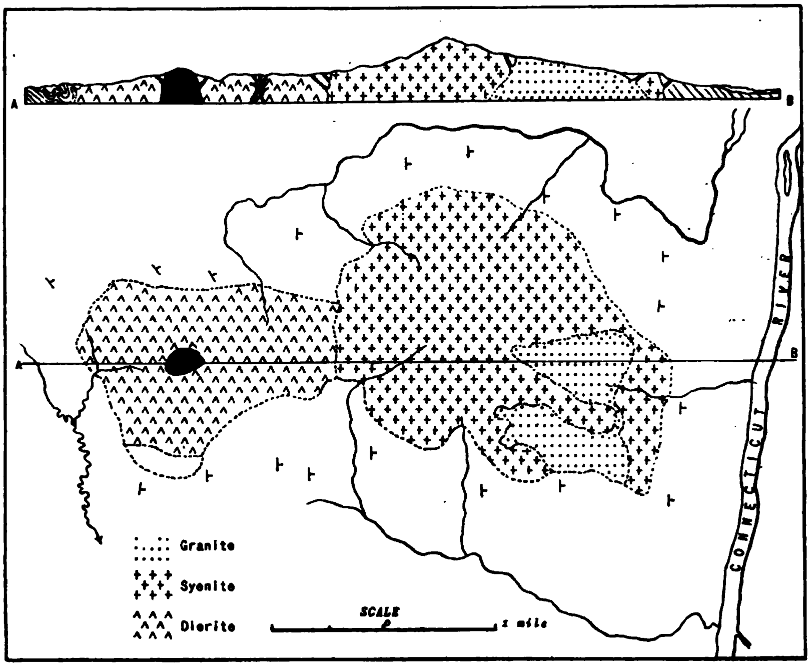

FIG. 8

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[1] *Sitzungsberichte der Wiener Akademie*, Vol. CIV (1895), p. 52.

[2] Compare Chamberlin and Salisbury, *op. cit.*, p. 477; and W. Salomon, Tschermak's *Mineralogische und petrographische Mittheilungen*, Vol. XVII (1897), p. 31.

associated directly with any particular theory of intrusion. There is pressing need for such a term signifying these large bodies, and one that will not commit the field worker to any theory of origins. The later use of the term "batholith" is therefore to be commended, as it renders that term much more useful in actual field descriptions where these cannot be accompanied with certain proofs of the *Durchschmelzung* theory as there applicable. In the proposed classification of intrusives the term "batholith" will have the meaning just noted.

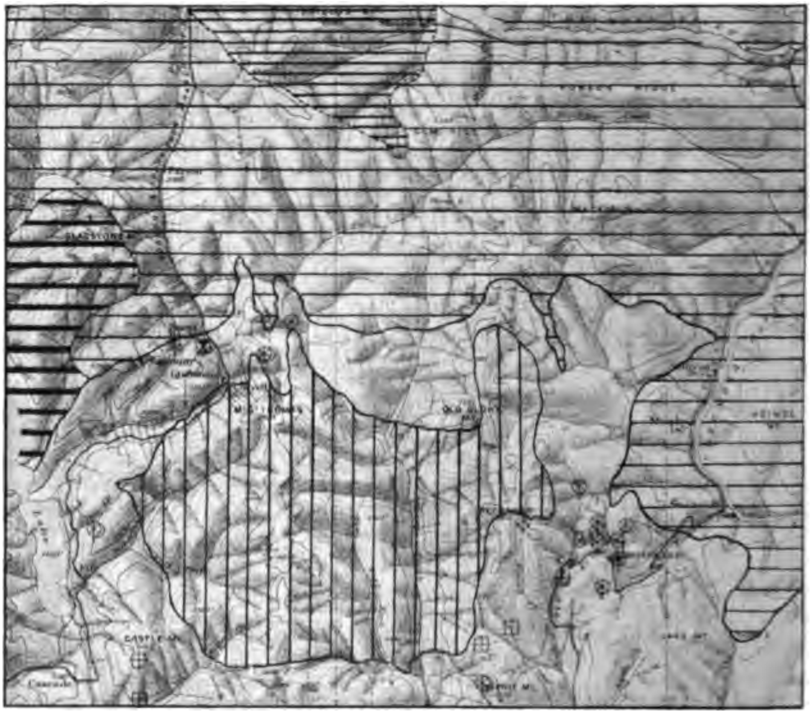

FIG. 9

A *simple batholith* is one composed of material intruded in one period of intrusion. (Fig. 9).

A *multiple batholith* is one composed of material demonstrably intruded in two or more periods of irruption, the material having been derived from the same kind of magma.

A *composite batholith* is one composed of materials demonstrably intruded in two or more periods of irruption, the materials being originally derived from two or more kinds of magma. (Fig. 9.)

A multiple or composite batholith may thus be in part made up of stocks.

Magmatic differentiation or other influences may render heterogeneous the material composing a simple batholith; or each member of a multiple or a composite batholith.

No author has attempted to fix a lower limit to the areal dimensions of a batholith. Since there is no certain distinction either in form or relations between stocks and batholiths, an arbitrary limit may be set between the two on the score of areal extent. It may be proposed that a body of the kind exposed in an area of less than 200 square kilometers is a stock; a similar body with a larger area is, accordingly, a batholith.

PRINCIPLES OF CLASSIFICATION

A review of the foregoing definitions shows that each of them has been based on one or more primary features of igneous intrusions, namely:

a) The method of intrusion.

b) The relation of the body to pre-intrusion structures in the invaded formation.

c) The form of the body.

d) The size of the body.

e) The attitude of the body with reference to the horizontal plane.

For a given body the method of intrusion is the most important criterion that could be used in classification. If it might be determined in every detail just how the igneous mass reached its present position, the form of the body and its relation to structural planes in the country-rock would therewith be known. A genetic, and therefore natural, classification should thus be founded on the method of intrusion. In the present state of geological science it is, however, impossible to apply this fundamental principle throughout the established list of intrusive bodies.

The greater number of recognized types are those of bodies of magma which is exotic except for a small, variable portion of it due to contact fusion. In each of these cases the magma has come into its chamber through channels which have fed the growing body from larger, deeper-lying, generally invisible reservoirs. The chamber is due to a parting of the country-rock into which the magma is *in*jected. An injected body is thus one which is entirely inclosed within the invaded formations, except along the relatively narrow openings to the chamber where the latter has been in communication with the feeding reservoir.

On the other hand, stocks, bosses, and batholiths never show a true floor. They appear to communicate directly with their respective magma reservoirs. Each of these bodies shows field relations suggesting that it is a *part* of its magma reservoir. The communication with the magmatic interior of the earth is not established by narrow openings, but by a huge, downwardly enlarging opening through the country-rock. In relation to the invaded formations a stock, boss, or batholith is intrusive, but is *subjacent* rather than injected.

How a magma reservoir is enlarged by the volume represented in the amount of intrusion signalized on the contacts of stock or batholith is a matter permitting as yet of no absolute certainty. In separating intrusive bodies into two primary divisions, one including all injected bodies, the other including subjacent bodies, a classification will do good service in emphasizing the need of further investigation into the mechanics of intrusion. No one has yet proved that any granite mass over 200 square kilometers in area, and characterized by vertical or outwardly sloping contact surfaces, is due to injection. Whatever may be the probabilities, no one has yet proved that such a mass has been intruded by any kind of assimilation of the invaded formations. Some light has been shed on the origin of batholiths and stocks, but they are certainly not understood as are dikes and sills.

So far as the method of intrusion is concerned, therefore, stocks, bosses, and batholiths belong to a primary division of intrusive bodies which may be defined as not demonstrably due to injection. The principle is negative; it leaves the method of intrusion unstated, but it brings into clear relief a principal contrast subsisting between the greatest of intrusions, on the one hand, and dikes, sheets, laccoliths, etc., on the other.

The other principles of classification—viz., *b*), *c*), *d*), and *e*)—are applied in the classification now to be presented in a manner sufficiently obvious to need no discussion. Principle *e*) is less fundamental than the others, excepting *d*,) and is recognized as appearing only occasionally in the scheme: the major diameters of true laccoliths tend to horizontality; a principal axis of a bysmalith, neck, stock, boss, or batholith is characteristically vertical.

It is obvious that transitional forms are to be expected among the related types of the classification. These forms have not been mentioned in the table, which would thus have become overburdened. Magmatic differentiation within the chambers of dikes, sills, stocks, etc., has often produced varietal types of these bodies, but the process has occurred too irregularly to permit of its furnishing a convenient criterion for the general classification.

PROPOSED CLASSIFICATION OF IGNEOUS INTRUSIVE BODIES

A. *Masses due to injection of exotic material.*
 I. *Injection along planes of stratification in invaded formation.*
  1. Intrusive sheets.
   a) Sills.
    (1) Simple.
    (2) Multiple.
    (3) Composite.
   b) Interformational sheets.
  2. Laccoliths.
    (1) Simple.
     Symmetric.
     Asymmetric.
    (2) Compound.
    (3) Multiple.
    (4) Composite.
    (5) Interformational.
 II. *Injection across planes of stratification in invaded formation.*
  1. Dikes.
    (1) Simple.
     Dike-networks.
    (2) Multiple.
    (3) Composite.
  2. Eruptive veins.
   Contemporaneous veins.
  3. Apophyses or tongues.

4. Bysmaliths.
5. Necks.
6. "Chonoliths."

B. *Masses due to processes other than injection; subjacent bodies.*

1. Stocks and bosses.
    (1) Simple.
    (2) Multiple.
    (3) Composite.
2. Batholiths.
    (1) Simple.
    (2) Multiple.
    (3) Composite.

NOTE.—Through oversight the "explanations" of the figures in the text were omitted.

EXPLANATIONS OF FIGURES

FIG. 1.—Diagrammatic map of a composite dike in Arran.

(After Judd, *Quarterly Journal of the Geological Society*, London, Vol. XLIX (1893), p. 545.)

1. Country rock (granite).
2. Augite andesite.
3. Quartz-felsite.
4. Pitchstone-porphyry.

The andesite was intruded along a fissure in the granite; then the felsite and porphyry were in succession intruded along the middle plane of the andesite dike.

FIG. 2.—Section of the Moyie Sill, British Columbia, at the crossing of the Moyie River and International Boundary.

Illustrating a body which has the form and relations of a true sill, although the thickness is more than 2,500 feet.

FIG. 3.—Section of a composite sill in the island of Skye.

(After Harker, *Tertiary Igneous Rocks of Skye*, 1904, p. 204.) The stratified Lias was cut by the sill of basalt; a later sill, of granophyre, was intruded along the middle plane of the basic sill. The latter itself may have been double.

FIG. 4.—Section of a composite laccoclith.

(After Harker, *op. cit.*, p. 209.) The black is basalt, the white, granophyre. The laccolith cuts heavily bedded lava flows. The maximum thickness of the laccolith is 150 feet.

FIG. 5.—Section of an interformational laccolith.

(After Weed and Pirsson, *Journal of Geology*, Vol. IV (1896), p. 412.) The floor of the porphyry laccolith (in black) is composed of Pre-Cambrian crystalline schists: the cover, of Palæozoic sediments. The length of the section represented is about ten miles.

FIG. 6.—Section of a typical volcanic neck.

(After Geikie, *Ancient Volcanoes of Great Britain*, Vol. II. p. 273.)

FIG. 7.—Diagrammatic map of a Tertiary "chonolith" of rhombenporphyry (crosses).

Cutting intensely folded Palæozoic sediments (broken lines) and Tertiary sandstones and conglomerates (white), occurring on the Kettle River, British Columbia. At its northern end the porphyry disappears under a late Tertiary lava-cap (stippled). The Tertiary sediments are tilted and faulted. The faulting was accompanied, or immediately followed, by the intrusion of the porphyry which field evidence shows to have been injected as a body with a highly irregular form.

FIG. 8.—Diagrammatic map and section of Ascutney Mountain, Vermont.

Illustrating a composite stock, composed of successive intrusions, in stock or boss form, of diorite, syenite, and granite. A small boss of syenite (shown in black) cuts the diorite. These bodies cut crystalline schists, the attitude of which is indicated by the conventional symbol for strike and dip.

FIG. 9.—Map of part of the West Kootenay District, British Columbia.

Illustrating a small batholith of syenite (vertical lining) and the southern edge of the great composite batholith of the district. The latter is made up of the "Nelson granite" (thin, widely spaced, horizontal lines), cut by the younger "Rossland Alkali granite" (more closely set horizontal lines) and by the "Valhalla granite" (heavy horizontal lines). The maximum east-west width of the smaller batholith is fifteen miles.

~~Hb 704.2.5 (Daly)~~

With the Compliments of the Author.

[From The American Journal of Science, Vol. XXVI. July, 1908.]

THE MECHANICS OF IGNEOUS INTRUSION.

THIRD PAPER.

By Regnald A. Daly.

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Art. III.—*The Mechanics of Igneous Intrusion.** (Third Paper;) by Reginald A. Daly, Massachusetts Institute of Technology, Boston.

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Introduction.—In the April and August numbers of this Journal in the year 1903, the writer published papers outlining the hypothesis of magmatic stoping as explanatory of the rise of batholithic magmas in the earth's crust. The hypothesis had taken form in his mind after some ten years of perplexity as to the mode of intrusion which has actually characterized granite bodies. In Vermont, New Hampshire, British Columbia and other regions he had met with this urgent and important field-problem. Everywhere the facts derived from field observations were, in principle, the same; the method of intrusion seemed, for each batholith or stock, to be the same. Since the writing of the two papers the writer has studied in some detail a dozen other large batholiths and as many typical stocks occurring on the southern boundary of British Columbia. For all of these also the stoping hypothesis appears to afford the truest explanation of the mode of intrusion.

Quite independently Barrell arrived at a similar hypothesis, as he attacked, in 1901, the problem of the "Marysville batholith" in Montana. Unfortunately his monograph was delayed in publication until 1907, so that it is only quite recently that geologists have had the benefit of this brilliant and thorough study of intrusive mechanism.† Barlow and Coleman have noted their belief in the efficiency of stoping as an intrusive process.‡ At the other side of the world, Andrews has described the great intrusive masses of New South Wales,

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† U. S. Geol. Surv., Prof. Paper No. 57, 1907.

‡ A. E. Barlow, Ann. Rep. Geol. Surv. of Canada, xiv, Part H, p. 79, 1904; A. P. Coleman, Jour. of Geol., xv, p. 773, 1907.

Am. Jour. Sci.—Fourth Series, Vol. XXVI, No. 151.—July, 1908.

and most forcibly shows the value of the stoping hypothesis and of its implied principles in explaining the rocks and field-relations in that state.*

Notwithstanding the support given the hypothesis by the work of these and other observers, the main conception has not met with favor from many working geologists.† A number of objections have been raised, most of which were discussed in the first two papers of this series. Within the last five years an unusually large amount of experimental data has been added to the confessedly meager store of known facts concerning the physics of rocks and rock-melts. These laboratory results, when fairly interpreted, seem to the writer to dispose of most of the objections. Other objections fall away as soon as they are confronted with the indisputable, long-known facts concerning rocks and igneous magmas. A third class of the objections are more stubborn and still remain among the frank difficulties of the stoping hypothesis. It is, however, the writer's belief that these difficulties are small when compared to those adhering to the older theories of batholithic intrusion.

In this third paper some of the more significant, newer contributions of the experimental laboratory to the matter at issue will be noted and discussed. In the light of the whole body of fact as understood by the writer, he will attempt to make clear the reasons why the various criticisms against the stoping hypothesis do not seem fatal to its acceptance. Finally, a new statement of certain important corollaries and tests of the hypothesis will be offered. In their discussion a certain amount of speculation seems not only warranted but necessary. It is obvious that the basis of any theory of the igneous rocks must, in part, consist of speculative assumptions; for every fruitful theory must deal with the earth's invisible interior. Neither petrology nor geology can afford to leave the problem of the earth's interior "to the poets." The advances of modern chemistry have largely been made possible through constructive speculation as to the nature of molecule and atom; yet molecule and atom are as inaccessible as the core of the earth. In the nature of the case we can never hope to arrive at the final explanation of igneous-rock bodies without building and testing hypotheses of materials and processes in and under the earth's "crust." Not only petrology but, in marked degree, mining geology is awaiting a stable theory of batholithic intrusion, since upon it must largely depend sound petrogenic and minerogenic theory.

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* E. C. Andrews, Records, Geol. Surv., N. S. Wales, vii, Pt. 4, 1904, and viii, Pt. 1, 1905.

† Cf. Science, xxv, p. 620, 1907.

Like the first and second papers, this one does not present a complete discussion of the different topics. On another occasion the writer may publish a fuller statement of the favored solution of the complex problem.

Hypothesis of magmatic stoping.—The essential points are the following:

1. Each acid, batholithic magma has reached its present position in the earth's crust largely through the successive engulfment of suites of blocks broken out of the roof and walls of the batholith.
2. The blocks (xenoliths) are completely immersed in the magma, partly through the confluence of apophyses which have been injected on joints and other planes of weakness in the country-rock; more often the blocks represent the effect of shattering, due to the obviously unequal heating of the solid rock at magmatic contacts.
3. The sunken blocks must be dissolved in the depths of the original fluid, magmatic body, with the formation of a "syntectic,"* secondary magma.
4. The visible rock of each granite batholith or stock has resulted from the differentiation of a syntectic magma.

In applying the hypothesis to the explanation of actual field-occurrences other general considerations seem necessary. Stoping and abyssal assimilation on the batholithic scale are begun by a primary basaltic magma. This magma carries the heat required for the double action.† The source of the magma is to be found in a general basaltic substratum beneath the earth's solid crust. The crust is considered as composed of two shells. The lower shell is capable of injection by huge masses from the substratum, which retains open communication with the injected bodies. The latter are regarded as then stoping their way up into the overlying shell, in which the resulting derivatives of the syntectic magma are the visible batholithic granites and allied rocks.

These subsidiary elements of the problem here to be discussed have been described in the first intrusion paper and, more fully, in a later communication on "Abyssal Igneous Injection."‡ No one of these additional conceptions is essential to the idea of stoping *per se.* All of them may prove incorrect without invalidating the stoping hypothesis in its main feature. Combining them and the idea of stoping, the writer has constructed a general working hypothesis for the origin of the igneous rocks. It seems, therefore, expedient in the present paper to discuss the problem in its larger aspect.

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* This very convenient name for a magma rendered compound by assimilation or by the mixture of melts, has been proposed by F. Loewinson—Lessing, Comptes Rendus, 7^{e} session, Congrès géol. internat. St. Petersburg, 1899, p. 375.

† Whether the substratum is actually or only potentially fluid is not a vital question in this connection. T. J. J. See, as a result of his calculations, holds that the earth's interior may be fluid. He explains the observed rigidity of the planet as due not to its being a true solid but to the direct influence of gravity, which binds the earth-shells so effectively that bodily tides are almost wholly prevented. In any case rigidity and solidity are not synonymous terms. Cf. T. J. J. See, Astron. Nachrichten, v. clxxi, p. 378, 1906.

‡ This Journal, vol. xxii, 1906, p. 195.

Field Relations of the typical batholith.—A principal fact on which the stoping hypothesis is based has been amply illustrated in the published descriptions of granite stocks and batholiths. Most, if not all, of these bodies in their accessible portions have replaced nearly equivalent volumes of the respective country-rocks. They are generally cross-cutting bodies. Their roofs are rough domes or arches, from which large masses of the invaded rocks are sometimes pendant into the crystallized granite. In each of many cases erosion has destroyed much of the roof, and the roof-pendants, still preserving the regional strike of their structure planes, are to-day exposed in section at the erosion-surface. Between the pendants and between the main walls of a large batholith, hundreds of cubic kilometers of country-rock formations are plainly missing; their place has just as plainly been taken by the granite.

A second principal fact is that, so far as granite batholiths and stocks are known, each of these bodies shows a cross-section enlarging with depth.* No one of them has yet exhibited a floor composed of older formations. In relation to visible country-rocks, all of them may be classed as subjacent, rather than as injected, bodies. In relation to the wall-rocks ten or more kilometers below the earth's surface, each batholith may have been truly injected as a kind of gigantic dike, but of this there is no direct proof. The actual observations in the field show unequivocally that the batholithic magmas have worked their way up by replacing and absorbing the country-rocks through the last few kilometers of ascent. Batholiths are not laccoliths.

A third generally observed fact is worthy of special attention. Where erosion has been profound the ground-plan section of the typical stock or batholith is seen to be elliptical and the profile-sections, as already noted, show that the upper-contact surface of the intrusive is dome-shaped. Both in ground-plan and in vertical sections the contact-surface is relatively smooth. Apophysal offshoots do interrupt the wall-rock, but the main-contact lines as mapped on ordinary geological maps are characteristically flowing lines. Large-scale, angular projections of country-rock into a well uncovered batholith are comparatively rare. Such smoothness of main-contact surfaces is that which is to be expected on the stoping hypothesis. A projection of country-rock would suffer specially intense shattering by the magma, which would thus tend to destroy the projection and smoothen the wall of contact. The case is analogous to the familiar exfoliation on sculptured stone in great city fires; architrave, sill, abacus and plinth lose their corners, ornaments in high relief are rifted off, and flutings are effaced. Bowlders of disintegration through weathering furnish other analogies.

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*See the numerous sections of stocks and batholiths in Lepsius' "Geologie von Deutschland"; also Barrell's monograph cited, and the writer's paper on the Okanagan Composite Batholith, Bull. Geol. Soc. America, xvii, p. 330, 1906.

In detail of form as in the larger field-relations of the typical stock and batholith, therefore, we seem to have cumulative evidence in favor of the theory of replacement and especially in favor of the hypothesis of mechanical replacement. On the other hand, the more intimate becomes our knowledge of these field-relations, the more improbable the "laccolithic theory" becomes. Neither smooth, flowing contact-surfaces against a heterogeneous terrane, nor a general elliptical ground-plan, nor an invariable downward enlargement are expected to characterize a batholith if it is simply a huge laccolith.

These summary statements are founded on the writer's field-experience, and on a tolerably wide study of the geological literature relating to granitic intrusions. The essential idea of replacement rather than displacement is far from new; it has been a lasting merit in the able work of Barrois, Michel Lévy, Lacroix and others, that they have persistently held to this fundamental fact of field-occurrence. Yet there are to-day many working geologists who just as persistently refuse to recognize the fact of the field. The chief reason for this refusal has undoubtedly been that the replacement of the country-rocks has, until recently, been attributed to their progressive solution on the main contacts—in other words, to marginal assimilation. The patent difficulties of this one view have prevented many, perhaps most, geologists from subscribing to the conclusions of their French colleagues. The proved insufficiency of the marginal-assimilation hypothesis has thus discouraged belief in that kind of replacement, but it by no means alters the fact of magmatic replacement. On the other hand, this fact will stand, no matter what theories of intrusion may prevail.

So far as recorded, the stoping hypothesis is the only one which recognizes the progressive assimilation of country-rocks as the magma rises in the crust, and, at the same time, explains the common lack of chemical sympathy between granites and their respective wall-rocks. By this hypothesis the preparation of the upper and visible part of the magmatic chamber is largely a mechanical process, working along main contacts; the solution of the engulfed blocks is effected far down in the depths of the magma—by abyssal assimilation. The resulting syntectic magma may thus be in strong chemical contrast with the adjacent wall-rock at any one level. Marginal assimilation is not excluded but is considered as an accessory and subordinate phase in the act of replacement.

Contact-shattering.—It has been objected that rocks are good conductors of heat and that, therefore, strong temperature differences with resulting rending strains are not to be expected in the shell of country-rock immediately surrounding a batholithic magma. This objection has been recently made by an expert physicist now specially engaged on petrological problems, and evidently needs consideration.* The following table of coefficients of absolute conductivity seems, however, to show, on the contrary, that rock-matter is far from being ranked as a good conductor. The table has peen made by compiling the values noted in the Landolt-Börnstein's Physikalisch-chemische Tabellen (1905 edition) and in Winkelmann's Handbuch der Physik. The values for the rocks are of the order expected in view of the familiar proofs of the extremely slow cooling of lava-flows.†

	k
Silver, about	1·0000
Copper, "	·9480
Lead	·0836
Quartz	·0158
Marble	·00817
Granite	·00757 –·00975
Gneiss	·000578–·00817
Sandstone	·00304 –·00814
Basalt	·00673
Syenite	·00442
Glass	·00108 –·00227
Water, about	·00130
Paper	·00031
Flannel	·00023
Silk	·00022
Cork	·00013
Feathers	·0000574

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* Cf. A. L. Day, Science, xxv, p. 620, 1907.

† The steepness of the possible temperature gradient in the wall-rock is shown by the fact that, a few days after lava ceases flowing, one can walk on its crust, although the lava just below is at red heat (700°-950° C.) or is yet hotter. For many hours or for several days the gradient at the surface may equal or surpass 500° C. per foot.

In the manufacture of calcium-carbide a mixture of limestone and coke is submitted to the action of a powerful electric arc. At the end of a furnace-run (about fourteen hours in the plant at Ottawa, Canada) the flow of heat is nearly steady and the temperature gradient in the furnace is about 3000° C. per foot. In this case the diffusivity of the limestone-coke mixture in the interior of the thoroughly heated furnace must be well below 60 in the Kelvin system of units.

Weber has found that k for gneiss at 0° C. is 0·000578 and at 100° C. 0·000416, showing a very great lowering with increase of temperature.[*] In fact, through the interval 0°–100° C., k seems to vary about inversely as the absolute temperature.[†] If this law should hold to 1100° C. the conductivity of average rock at 1100° falls to about 0·001—nearly the value for water, which is famous as a poor conductor.

In the present connection the thermal diffusivity (κ) of rock, rather than its conductivity, is of first importance. If s = specific heat and d = density, we have

$$\kappa = \frac{k}{s.d}$$

For rock at room temperature (20° C.) Kelvin assumed 400 as the value of κ when the unit of length is a foot, the unit of time a year, and the unit of temperature one degree Fahrenheit. This value is close to that which represents the average of the determinations made for different rocks at room temperatures, during the years since Kelvin wrote his famous essay.[‡]

If κ be assumed as 400 at all temperatures up to 1300° C., it is possible to calculate the temperature gradient in the wall-rock of a molten batholith at the end of specified periods of time. For practical purposes the surface of contact may be regarded as infinite; let it further be considered as plane. Under these conditions the following Fourier equation furnishes the datum for calculating the temperature at a point x feet from the contact at the end of t years.[§] In the equation b = the temperature of the magma; c = the temperature of the wall-rock assumed as initially uniform; and u = the required temperature. We have:—

$$u = b + (c - b) \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{\kappa t}}} e^{-\beta^2} \, d\beta.$$

For values of $\frac{x}{2\sqrt{\kappa t}}$ which are less than 2·6 the value of the integral can be readily found from the table of the probability integral which appears in standard text-books on the Method of

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[*] Values taken from Landolt-Börnstein Phys.-Chemische Tabellen. Forbes and Hall have proved analogous relations for iron and for magnesium oxide; cf. J. D. Forbes, Trans. Roy. Soc. Edinburgh, xxiv, p. 105, 1867, and E. H. Hall and others. Proc. Amer. Acad. Arts and Sciences, xlii, p. 597, 1907.

[†] Cf. P. G. Tait, Recent Advances in Physical Science, 2d ed., London, p. 270, 1876.

[‡] Trans. Roy. Soc. Edinburgh, 1862.

[§] Cf. W. E. Byerly's Elementary Treatise on Fourier's Series, Boston, 1893, p. 86.

Least Squares. For higher values of $\frac{x}{2\sqrt{\kappa t}}$ the value of the integral can, in many cases, be computed by developing it into a series. Kelvin's value for κ is peculiarly favorable for such computation and the corresponding units have been used by the writer in the calculations.

Let b = 2200° F. (about 1200° C.); c = 400° F. (about 200° C.); t = 1, 4, 16, and 100 years; and let x have the different values shown in the left-hand column of the following table (I) The corresponding temperatures are shown in the other columns.

TABLE I.—Showing values of u when κ = 400 and

x	t = 1 year.	t = 4 years.	t = 16 years.	t = 100 years
0′	2200° F.	2200° F.	2200° F.	2200° F.
10′	1703	1947	2074	
20′	1263	1703	1947	
40′	683	1263	1703	
80′	408 5	683	1263	
100′	ca.400	537	1078	1703
160′	400	408·5	683	
200′	400	ca.400	537	1263
320′	400	400	408.5	
400′	400	400	ca.400	683

The table shows that, at the end of the first year, the temperature of the rock is but slightly affected by the magmatic heat at a point 80 feet from the contact, and that the temperature gradient for the 80-foot shell then averages nearly 23° F. per foot. At the end of four years the temperature is but slightly affected at a point 160 feet from the contact and the temperature-gradient is about 11° F. per foot.

But κ cannot be nearly so great as 400 in the case before us. We have seen that k decreases rapidly with rise of temperature in rock. The experiments of Weber, Bartoli, Roberts-Austen and Rücker, and Barus show that the specific heat of rock averages about ·180 at 20° C. and increases regularly with rise of temperature, so that at 1100° C. the specific heat averages about ·280.* It follows that thermal diffusivity in rock decreases with rising temperature even faster than the conductivity decreases. At 1100° C., κ may, indeed, be only

$$\left(\frac{\cdot 180}{\cdot 280} \times \frac{293}{1373} \times \frac{1\cdot 000}{\cdot 973} = \right) 0\cdot 141$$

or less than one-seventh, of the diffusivity at 20° C. For rock heated to 1000° or 1200° C. κ is, thus, probably not much more than 60 in the Kelvin system of units.

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* For references see J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter, I. math.-naturv. Klasse, No. 1, p. 40, 1904.

It seems safe to assume, first, that the diffusivity of the gradually heated wall-rock may vary from 275 or less to 100 or 150; secondly, that the average diffusivity of an 80-foot shell heated during the first year by adjacent molten magma, will be no greater than 200. If κ be regarded as averaging 200 for all periods greater than one year, the four columns showing values of u in the table will serve if t is, respectively, 2, 8, 32 and 200 years.

As a result of somewhat rigorous calculation, then, it appears certain that the heating of wall-rock by plutonic magma must progress with great slowness and that the resulting temperature gradient in the shell adjoining the molten magma must be steep for many years after the original establishment of the contact.*

Further, Less has proved that rocks have highly variable coefficients of conductivity, some species possessing coefficients twice as high as those of other species.† It is also well known that bedded or schistose rocks conduct heat along and across their structure-planes at quite different rates. Where, therefore, the wall-rocks about a batholithic mass are heterogeneous, the heat-conduction is variable and expansional stresses must ensue.

A rough calculation of the enormous stresses involved in all these processes of differential heating was published in the second paper of this series, where also an account is given of the practical use which has been made of such stresses in primitive quarrying.‡ Every great city conflagration leaves manifold evidences of the shattering effects of the one-sided heating of a rock-mass—in columns, sills, and cornices of granite or sandstone.

There seems, therefore, to be a sheer necessity for believing in contact-shattering through differential heating and expansion in the thin shell of a country-rock which encloses a large body of molten magma. The evidence for the shattering is often exceedingly full and clear in the field. The broad or narrow belts of xenoliths so often found just inside the main contacts of batholiths are very hard to explain if those batholiths are due to laccolithic injection. The blocks are characteristically angular; they are generally not arranged with their longer axes parallel, as if they had been pulled off from the walls by the friction of the moving magma. On the laccolithic theory one would expect many of the xenoliths to form elongated smears in the granite rock. This is indeed occasionally seen but most exceptionally; as a rule the xenoliths have just that irregularity of form and arrangement which they should have if they had been shattered off by the hot magma just before its final consolidation. Throughout its long, earlier history the magma must, in every case, have had a much more effective shattering power.

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* By using the same Fourier equation it is not difficult to show that the loss of thermal energy which a magma suffers by conduction into the country-rock is relatively small, even after the lapse of two or three hundred thousand years. The long duration of the magmatic period in a slightly superheated plutonic mass of large size becomes easily understood.

† Phil. Trans., vol. clxxxiii A, p. 481, 1892.

‡ This Journal, xvi, p. 112, 1903; cf. Ann. Rep. State Geologist of New Jersey, 1906, p. 17.

It may be noted that the shattering of crystals and rock-fragments, when immersed in silicate melts, has often been observed.* The strains are, in such cases, necessarily of a lower order than those developed on the wall of a batholith where, therefore, shattering is even more certainly brought about.

Relative densities of magma and xenolith.—In his first intrusion-paper, the writer published the results of his attempt to calculate the possible specific gravities of the chief types of molten magmas under plutonic conditions. The calculations were based on Barus's well-known fusion experiments on diabase. The specimen investigated had a specific gravity of 3·0178; when fused to a glass and cooled to 20° C., a specific gravity of 2·717. He further states that the glass† showed an expansion of 3·9 per cent in "melting" and, as glass, expanded 0·000025 in volume for a temperature rise of 1° C. through the interval 0°–1000° C. and 0·000047 in volume for 1° C. through the interval 1100°–1500°. The "melting" expansion (solidification-contraction) and the varying rate of expansion (or contraction) above and below 1000° C. seem to show that some crystallization of the melt took place during the experiment. Such crystallization was inevitable under the conditions of the experiment, in which the cooling lasted several hours. Barus's curves do not, therefore, show directly the volume changes suffered by pure diabase glass in passing from the molten isotropic state to the rigid isotropic state at room temperature. Excluding the "solidification" contraction, the glass loses but 3·5 per cent of its volume in passing from the molten state at 1400° C. to room temperature; the loss of volume through the same temperature interval was calculated in the first paper as about 8 per cent. Barus found that the net decrease in specific gravity in passing from rock at 20 C. to glass at 20° C. was 10 per cent. For his diabase specimen, therefore, the decrease of specific gravity in passing from 20° C. to molten condition at 1200° C. is possibly only about 13 per cent, instead of about 16 per cent, as noted in the first paper.*

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* Cf. C. Doelter and E. Hussak, Neues Jahrb. für Min. etc., 1884, p. 18; A. Becker, Zeitschr. d. d. geol. Ges., xxxiii, p. 62, 1881.

† "Throughout this paper the molten rock solidifies into an obsidian." C. Barus in Bull. 103, U. S. Geol. Surv., p. 26, 1893.

Quite recently J. A. Douglas has made a number of very careful measurements of the densities of typical igneous rocks and of their respective glasses, all specific gravities being taken at room temperatures.† Douglas's method is reliable and his results accordant. For gabbro he found the decrease of specific gravity, in passing from rock to glass, to be 5·07 per cent. Delesse had found the decrease to be 11·46 per cent, as the average of measurements of two specimens from different localities Barus's determination, 10 per cent, is intermediate between the two.

It seems probable, therefore, that a decrease of 6 per cent in specific gravity (rock to glass at 20° C.) is close to the minimum for the average gabbroid rock, and it is possible that Barus's 10 per cent decrease is too high for average gabbro. For present purposes it is safer to use the minimum value of 6 per cent. Similar minima for diorite (6 per cent), quartz diorite and tonalite (7 per cent), syenite (8 per cent) and granite (9 per cent) have been estimated from the numerous measurements of Delesse, Cossa and Douglas. Each of these rocks certainly

Table II.

	Specific gravity of Crystalline rock at			Specific gravity of same rock when molten at			
	20°C.	1000°C.	1300°C.	1000°C.	1100°C.	1200°C.	1300°C.
Gabbro and diorite	2·80	2·73	2·71	2·57	2·56	2·54	2·53
	2·90	2·83	2·80	2·66	2·65	2·64	2·63
	3·00	2·92	2·90	2·75	2·74	2·73	2·72
	3·10	3·02	3·00	2·84	2·83	2·81	2·80
	3·20	3·12	3·10	2·94	2·92	2·91	2·91
Quartz-diorite and tonalite	2·70	2·63	2·61	2·46	2·45	2·44	2·43
	2·80	2·73	2·71	2·54	2·53	2·51	2·51
Syenite	2·60	2·54	2·52	2·33	2·32	2·31	2·31
	2·70	2·63	2·61	2·42	2·41	2·40	2·40
	2·80	2·73	2·71	2·52	2·51	2·50	2·50
Granite and gneiss	2·60	2·54	2·52	2·31	2·30	2·29	2·29
	2·70	2·63	2·61	2·40	2·39	2·39	2·38
	2·80	2·73	2·71	2·49	2·48	2·47	2·47

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* Bischof, in 1841, found that basalt expanded 7 per cent in passing to a glass at room temperature, and 10·4 per cent in becoming molten. (Quoted from Zirkel's Lehrbuch der Petrographie, 2d ed., 1893, vol. i, p. 683.)

† Quart. Jour. Geol. Soc., xiii, p. 145, 1907.

expands in the interval 20°–1300° C. as much as 0·000025 volume per degree Centigrade (Barus and Reade—see first paper). This average may safely be employed as a means of determining the minimum decrease of density which each rock-type undergoes in passing into the molten condition. On this basis the writer has constructed the preceding table (II), which shows the changes of specific gravity at convenient temperature intervals.

Table III shows the changes in specific gravity undergone by blocks of stratified and schistose rocks (common country-rocks about batholiths), as these blocks assume the temperature (1300° C.) of molten magma in which they are immersed.

TABLE III.

	Range of sp. gr. at 20°C.	Range of sp. gr. at 1300°C. (solid)
Gneiss	2·60–2·80	2·52–2·71
Mica schists	2·75–3·10	2·67–3·00
Sandstone	2·20–2·75	2·13–2·67
Argillites	2·40–2·80	2·32–2·71
Limestone	2·65–2·80	2·57–2·71

It appears from these tables that nearly all xenoliths must sink in any molten granite or syenite; most xenoliths must sink in molten quartz-diorite, tonalite or acid gabbro. Many xenoliths might float on basic gabbro but the heavier schists and gneisses must sink in even very dense gabbro magmas at 1300° C.

Giving, then, the highest permissible values to the specific gravities of magmas, it is still true that blocks, such as are shattered from the wall or roof of a batholith, must sink when immersed in most magmas at atmospheric pressure. As shown in the first intrusion paper, the blocks would likewise sink, though the magma enveloping them lies at depths of ten or fifteen kilometers below the earth's surface.

Sinking of the shattered blocks—It has been objected to the stoping hypothesis that the viscosity of granitic magmas is too great to allow of the sinking of blocks even much denser than those magmas.* This objection has, however, never been sustained by definite experimental or field proofs. The xenoliths visible along batholithic contacts have assuredly not sunk far from their former positions in wall or roof and the reason for this must be sought in the high viscosity of the magma. High viscosity is an essential attribute of a nearly frozen magma. The phenomena of fractional crystallization and of magmatic differentiation unquestionably show that each plutonic magma must pass through a long period of mobility. The most viscous of granitic magmas, the rhyolitic, issues at the earth's surface with such fluidity that the rhyolite often covers many square miles with a single thin sheet. The absolute viscosity of the Yellowstone Park rhyolites must have been of a low order when many of these persistent flows were erupted.[*]

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* Cf. W. Cross, G. F. Becker, and A. L. Day, Science, xxv, p. 620, 1907.

Even granting that the kinetic viscosity of a plutonic magma is thousands of times that of water, it seems inevitable that it could not support xenoliths more dense than itself. In a few days or weeks stones will sink through, and corks will rise through, a mass of pitch, the viscosity of which is more than a million of millions of times that of water.[†] Ladenburg has lately shown that small steel spheres will, in a few minutes, sink through twenty centimeters of Venetian turpentine, a substance 100,000 times as viscous as water.[‡] Ladenburg's experiments have verified the generally accepted equation expressing the rate of sinking of a sphere in a strongly viscous fluid:

$$x = \frac{2}{9} \frac{g r^2 (d - d')}{v}$$

were x = the velocity of the sphere when the motion is steady; g = the acceleration of gravity; d = the density of the sphere; d' = the density of the fluid; r = the radius of the sphere; and v = the viscosity of the fluid.[§] The equation shows that the velocity of sinking varies directly as the square of the radius of the sphere. This fact may be correlated with the observation so often to be made on granite contacts, that large xenoliths are rare. This apparently means that, at the end of the shatter-period, the viscosity is truly so high as to allow of the smaller blocks being trapped at high levels in the freezing magma, while the large blocks, with greater velocity, shall have sunk into the depths.

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[*] See Atlas accompanying Monograph 32 of the U. S. Geol. Survey. King described the great rhyolite flows of Nevada as bearing "abundant evidence of true fluidity at the period of ejection." U. S. Geol. Explor. 40th Parallel. Sys. Geol. 1878, p. 616.

Doelter has studied the behavior of a large number of crystalline rocks and minerals during fusion. His results show that the temperature-interval between the stage of softening and that of notable fluidity averages, for the basic rocks, about 50° C., and for the acid rocks, about 90° C. (Tscher. Min. u. Petrogr. Mitth. xx, p. 210, 1901.) The interval is not great and it certainly seems unsafe to deny that even the most viscous, because cooled, lavas were fluid in depth.

[†] Jamin et Bouty, Cours de Physique, tome I. 2e fascicule, Paris 1888, p. 135; cf. Daniell's Text-book of the Principles of Physics, 2d ed., London, 1885, p. 211.

[‡] Annalen der Physik, xxii, p. 287, 1907.

[§] Poynting and Thomson, Text-book of Physics, Properties of Matter. London, p. 222, 1902.

Doelter estimates that the pressure of from 7500 to 11,000 meters of rocks increases magmatic viscosity no more than 20 to 30 per cent.[*] If the increment be anywhere near this value we may be certain that the viscosity of superheated, plutonic magma is relatively low. Becker has calculated that the viscosity of a Hawaiian basaltic flow, not one of the most fluid, was, at eruption, about fifty times that of water. The more fluid rhyolite flows may have viscosity a thousand times greater than that of water. The corresponding viscosities of the same magmas when ten kilometers underground may, then, be possibly no more than from sixty to fifteen hundred times that of water. One must conclude that a xenolith, even very slightly denser than such a plutonic magma, must sink into it. Since such magmas necessarily cool with extreme slowness, there is evidently good ground for believing that an enormous amount of solid rock could be engulfed before practical rigidity is established. The average xenolith must sink in a less dense magma with the viscosity of pitch—yet how much more rapidly in magma possessing the low viscosity which is postulated in any of the ruling theories of plutonic-rock genesis!

Problem of the cover.—The stoping hypothesis presents an obvious principal difficulty; it refers to the apparent danger of the foundering of the roofs covering the larger batholiths. Under plutonic conditions (at depths of from three to ten kilometers) the average molten granite would have a specific gravity no higher than 2·40. The average rock of its roof has a specific gravity of about 2·70. If, then, through orogenic movement, a large mass of the roof-rock became once wholly immersed in the granite, it would not only founder itself but through subsequent buckling the whole roof might collapse and founder in sections. Such a catastrophe has almost certainly not happened in the case of any Paleozoic or later batholithic intrusion. This difficulty has been emphasized by Barrell, who has justly given it a prominent place in his monograph.[†] Lawson speaks of batholiths 100 miles in diameter and also finds the necessity of explaining their roof-support as a principal ground of unfavorable criticism.[‡]

The present writer cannot claim to have solved this problem, but he does not find it to form a fatal objection to the hypothesis. In the first place, it seems clear that all the other hypotheses of granitic intrusion are facing the same dilemma. All of them expressly or tacitly postulate some degree of fluidity in each granitic mass as it either replaces or displaces its country-rocks. We have seen that, though the viscosity of such a magma may be several hundred times that of water, the roof-sections, once immersed, must sink in the magma. All petrologists who believe in magmatic or other differentiation as operative in batholiths must face the common difficulty.

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[*] Physikalisch-chemische Mineralogie, Leipzig, p. 110, 1905.

[†] Op. cit., p. 172.

[‡] Science, xxv, p. 620, 1907.

Secondly, the writer has shown reasons for believing that the earth's crust at present rests on a continuous *couche* of basaltic (gabbroid) magma, either quite fluid or ready to become fluid when injected into the crust. If the average specific gravity of the crust is 2·75 (a probable value), it would as a whole be quite able to float on the basaltic *couche*, which, as noted in Table II, would probably have a specific gravity over 2·90. Imperfect as the numerical data are, we seem justified in concluding that the earth's crust is now, as a whole, in stable flotation.*

It may have been entirely different in pre-Keewatin (earliest Archean) time when the superficial, acid *couche* of the primitive earth began to solidify. Then foundering may have taken place, as Kelvin imagined, and the early formed crusts could have sunk a score of kilometers or more until they met the denser *couche* below. Possibly some of the complexity of the pre-Cambrian formation may be referable to this unstable condition of the early crust. Already in Keewatin times the acid shell was solidified and was then penetrated by basaltic injections which reached the surface, forming the heavy masses of greenstones belonging to that period. Since then the crust has remained essentially coherent, and through it the primary basalt has, at many times and places, been erupted. It is, however, quite possible that the lack of system among the axes of the Laurentian batholiths and the abundance of those batholiths are both explained by the thinness and weakness of the crust in post-Keewatin and pre-Cambrian time.

For Paleozoic and later batholiths there is a well-defined law that they have penetrated the crust only on the sites of folded geosynclinals, and that the larger batholithic axes are usually arranged parallel to the respective geosynclinal and mountain-range axes.

In other words, the intrusion-history of the globe may be conceived as divisible into three epochs: the first being that in which the outer primary shell was becoming stable through successive solidifications and founderings; the second being the post-Keewatin (Laurentian) epoch of very general interaction between the fluid basaltic substratum and acid crust, without extensive founderings but with development of many large, irregularly occurring batholiths; the third, a period of the localization of batholiths in certain mountain-built belts,

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*** For a further discussion of this point see this Journal, xxii, p. 201, 1906.**

where alone there seems, in this third period, to have occurred the injection of molten magma in masses of batholithic size—in no known case accompanied by wholesale foundering.

Again, granting the hypothesis that a visible post-Archean batholith is the acidified, upper portion of a basaltic body originally injected to a level less than about ten or fifteen kilometers from the earth's surface (perhaps the level of no strain), it is not difficult to see that extensive foundering may be impossible. Only after some differentiation or acidification of the primary magma would any part of it become less dense than the average roof-rock. Xenoliths of the heavier gneisses and schists would, however, sink. When dissolved in the primary magma their material—added to that dissolved along the main contact-surfaces—would lower the density and inaugurate the stage of general stoping. Only when the resulting syntectic magma has been formed in large amount is there any danger of roof-foundering. But it is evident that, in the process of dissolving the engulfed blocks, the magma is losing heat. In every post-Archean batholith the magma, because of exhaustion of the heat-supply, seems to have been arrested in its upward course at average distances of one or more kilometers from the earth's surface. The syntectic magma, less dense than the roof-rock, is thus necessarily of limited depth. That depth represents the thickness of the *couche* which endangers the stability of the roof. If, now, we imagine the buckling of the roof with the complete immersion and sinking of certain parts of it, the foundering must be limited by the width of the injected body (seldom over fifty kilometers) and by the thickness of the acid *couche* (ten kilometers or less). Extensive floods of rhyolite and allied rocks may have issued at the surface in consequence of partial foundering (faulting), but great crustal catastrophes involving large areas would not be expected.

Finally, it should be noted that post-Archean granitic intrusions have regularly followed periods of prolonged orogenic crushing, during which accumulated tangential stresses are effectually relieved. As the magmas work their way up into the folded terranes there is relatively little chance for the buckling of the roof. Until it is buckled and immersed in the magma it cannot sink. Now the heat of the magma, though it shatters the roof-rock at the immediate contact of solid and fluid, must tend to expand the roof, tighten it, prevent normal faulting and so strengthen the roof. The cover of the batholith is thereby kept in an exceptionally rigid condition. Its strength is, initially, that of a domed shell spanning diameters not very many times the thickness of the shell. The strength is increased, as with the groined roofs and arches of Gothic architecture, by the presence of roof-pendants; and by thermal expansion, the whole is strongly knit together. Immersion and foundering of roof-sections may, therefore, not have been possible in the case of post-Archean batholith or stock.

In spite of the highly theoretical nature of some of the foregoing argument, it appears to the writer to carry weight enough to warrant our regarding the difficulty in question as not destructive of the stoping hypothesis. The problem needs further study in connection with this and all other conceptions of granitic intrusion.

Supply of the necessary heat; magmatic superheat and its causes.—Whether the observed average temperature gradient within the earth's crust is to be explained as due to original heat (inherited from an early epoch in the development of the earth either from a gaseous or planetesimal nebula), or whether the gradient is due to the evolution of heat with the break-up of radium and other radio-active substances, are general questions not immediately affecting the stoping hypothesis. We need go no further back in the thermal problem than to secure an estimate of the minimum temperature of the primary magma when abyssally injected and thus prepared for stoping and assimilation. This estimate is evidently not easy to make. A rough idea of the probable temperature may be obtained by deductively considering the temperature gradient or, secondly, by assuming that the initial temperature of the abyssally injected basalt is not far from that of the hottest basaltic lava known in volcanoes.

The first method is only applicable on certain assumptions as to the thermal and material constitution of the basaltic substratum. It is first of all assumed that the substratum, though a true basalt for many kilometers of depth, is faintly stratified according to density differences. The chemical contrast between successive shells of the substratum may be extremely slight and yet sufficient to prevent convection-currents, even though the bottom shell of the substratum is several hundreds of degrees hotter than the uppermost shell. A rise in temperature of four hundred degrees involves an expansion of only about one per cent in volume. An underlying *couche* of basalt at 1600° C. would, therefore, if its specific gravity at 1200° C. were 2·93, not convectively displace an overlying *couche* of magma at 1200° C. and with a specific gravity of 2·90. Such faint density stratification, if assumed, goes far to explain the general stability of the earth's crust and so far is in accord with the facts of post-Archean geology. This conception also involves the possibility that the observed temperature gradient continues without important change, deep into the substratum. It is here also assumed that the gradient, 3° C. for 100 meters of descent, applies to the crust and to the upper part of the substratum at least. It must be noted, however, that the gradient may very considerably steepen in the depths, because of the fact that the thermal conductivity and diffusivity of rock both decrease in large ratio with increase of temperature. The amount of steepening of the gradient is unknown, but our ignorance on this point is unessential to the principle of the following argument, in which the normal gradient is assumed throughout.

Thirdly, it is assumed that, under normal conditions, the substratum shell immediately below the solid crust is not superheated but is at the melting-point of basalt at that depth. The accepted temperature gradient gives, at the depth of 38 kilometers, a temperature of 1140° C. Vogt has calculated that the pressure at this level raises the melting-point about 50° C. Since basalt at atmospheric pressure is just melted at about 1190° C., we may conclude that the bottom of the crust, in accordance with the assumptions, averages 38 kilometers below the present surface. If the earth is cooling down, the crust was evidently somewhat thinner during Tertiary and pre-Tertiary batholithic intrusion.

If, now, a broad geosynclinal prism of sediments, 10,000 meters thick in the middle, is laid down on the site of a future mountain-range, the isogeotherms must rise. The uppermost layer of the substratum, where most deeply buried, will thus tend to assume a temperature of nearly 300° C. above normal. If the sedimentary prism be folded and overthrust as in the usual large-scale orogenic disturbance, the substratum below the mountain-range may be still more effectively blanketed, with a further rise of the isogeotherms. Quickened erosion may, however, largely offset this thickening by the mountain-building process, and it would be unsafe to postulate a total rise of temperature of more than 300° C. in the substratum of the area. Part of this superheat is lost by conduction into the crust, the lower basic part of which may be thus melted. An unknown but possibly considerable fraction of the total superheat may remain in the original substratum, and this amount of superheat would characterize the basalt when rapidly injected into the crust.

In the partial release of pressure in the act of injection we have another, but probably less important, source of superheat—averaging some fraction of the 50° C. by which the melting-point is raised at the bottom of the 38-kilometer crust. A third source of superheat is found in the conversion into heat of the mechanical energy necessary for injecting a viscous melt into an opening cavity.

These three sources of superheat would alone furnish enough thermal energy to raise the injected basaltic magma from 1140° C. to some temperature short of 1500° C. or 1600° C.

The piling up of 10,000 meters of lava over a large area would have an analogous superheating effect on the substratum. This conclusion enables us to give some explanation of the fact that the lavas of Kilauea and Mauna Loa seem to be the hottest known in any volcanic vent. The vast Hawaiian lava-plateau has, apparently, been built up by the comparatively rapid effusion of basaltic flows from Pacific depths averaging 6,000 meters to heights above sea of about 4,000 meters. The unique lava-fountains of the calderas, while showing obvious evidence of considerable superfusion, are described as glowing with "white heat."* If a correct description, this implies a temperature of 1300° C. or possibly 1400° C.† Such temperature must be a minimum for the substratum which feeds the calderas, where there is continuous loss of heat in the convectively stirred lava.

Speculative argument and limited observations in nature agree, then, in fixing some such temperature as 1300° C. as a minimum for the basaltic mass injected into the crust-rock below a great mountain range.

Capacity of superheated, plutonic magma for melting and dissolving xenoliths.—Basalt must have a thermal capacity much like that of diabase at the same temperature. Barus's experiments show that the average specific heat of diabase for the interval 1300–1140° C. is ·350.‡ The heat-energy contained in the substratum, if it be superheated 160° C. above its melting-point (1140° C.), is in excess of that contained in the substratum just above its melting point by (160×·350=) 55+ gram-calories.

This surplus heat-energy is available for the fusion and assimilation of country-rock. There are good reasons for believing that the average wall-rock of granite batholiths has the composition and crystallinity of a granitoid gneiss. For purposes of calculation this will be assumed to be the fact. The average temperature of the wall-rock before an abyssal intrusion may be conservatively estimated from the normal temperature gradient to be 200° C. In order to raise the gneiss to the temperature of 1200°, where it is just molten, about 410 calories (assuming latent heat at 90 calories—a value estimated by Vogt for the silicates) per gram must be supplied from an outside source. If all the superheat of the basalt were available for melting (not dissolving) gneiss, $\frac{55}{410}$ of mass-unit of gneiss would be melted by mass-unit of the superheated basalt; or about 7·5 mass-units of the basalt would melt a mass-unit of wall-rock.

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* J. D. Dana, Characteristics of Volcanoes; New York, 1891, p. 200.

† LeChatelier and Boudouard's High Temperature Measurements; New York, 1904, p. 246.

‡ C. Barus, op. cit., p. 53. For the interval 100–20° C. the mean specific heat is about ·185. There is, in fact, a steady increase in the mean value as the temperature of any silicate or silicate mixture rises. This fact goes far to explain the prolonged liquidity of assimilating magmas. Cf. J. H. L. Vogt in Christiania Videnskabs-Selskabets Skrifter, math-naturv. Klasse, 1904, No. 1, p. 40.

Such simple melting would, however, not occur. There are plenty of field and laboratory proofs that molten basalt, even slightly superheated, will dissolve fragments of gneiss and allied rocks. The mutual solution of two contrasted silicate mixtures takes place at a certain temperature which is lower than the melting point of either one. The simple contact of two such materials suffices to cause their mutual solution at that lower temperature.* This fundamental law of physical chemistry has been experimentally demonstrated for silicates by Vogt and by Doelter and his pupils, although the last mentioned authors have, perhaps, not sufficiently regarded the fact that it takes considerable time for the mutual solution to take place.†

Petrasch has experimentally shown that, when two parts of limburgite and one part of granite are mixed and heated, they melt together at 950° C. and the solution remains fluid down to 850° C.‡ Predazzo granite softens at 1150° C. and the limburgite at 995° C.§ In this case, there is a lowering of 200°–300° below the melting-point of granite and 45°–145° C. below that of limburgite.

It seems highly probable, thus, that gneiss-xenolith and basalt would form a solution or syntectic film which is molten at a temperature *at least* 50° C. below the fusion-point of basalt at the average depth of ten kilometers or less below the earth's surface. At those depths basalt melts at about 1100° C.; the syntectic would be molten at or below 1050° C. If the syntectic film were continuously removed during the sinking of the block or by the currents inevitably set up during stoping, nearly all of the superheat of the basalt might be used in dissolving the gneiss. The total melting-heat of gneiss, if molten at 1050° C., would be about 400 calories. The heat-energy required for the solution of one gram of the gneiss which has an original temperature of 200° C. is (400−40=) 360 calories. The heat-energy given off by one gram of basalt in cooling from 1300° to 1050° C. is about ($250 \times \cdot 340 =$) 85 calories. One gram or mass-unit of gneiss would, then, be dissolved by $\left(\frac{360}{85}=\right)$ 4·3 grams or mass-units of the primary basalt, provided all the thermal energy were used for solution.

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*Cf. O. Lehmann, Wiedemann's Annalen der Physik, vol. xxiv, p. 17, 1885.

†See J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter math.-naturv. Klasse, 1904, No. 1, p. 191; and Tscherm. Min. u. Petrogr. Mitth., xxiv. p. 473, 1906.

‡K. Petrasch, Neues Jahrb. für Min., etc., Beil. Bd. xvii, 1903, p. 508. Petrasch mixed the powders of one part of granite (softens at about 1150° C.) with two parts of hornblende andesite (softens probably about 1050° C.) and found the mixture to become molten at 900° C., proving again an important lowering of the melting-point below that of either rock. Basic rock thus acts as a flux for granite (or gneiss) to an extent comparable with that proved by Petrasch and others for lithium chloride, calcium fluoride, ammonium chloride, sodium tungstate, etc.

§C. Doelter, Tscherm. Min. u. Petrogr. Mitth., xx, 1901, p. 210.

These various calculations are obviously very crude. They take no account of conduction of heat away from the batholithic mass, nor any account of possible exothermic or endothermic chemical reactions between basalt and wall-rock; nor any account of the influence of water, chlorides, etc., derived from the geosynclinal rocks which are assimilated.* These substances held in the magmatic solution tend to lower the solidification point of the syntectic. The result of the calculation would also be affected if we assume that the heavier xenoliths would sink to levels where the temperatures are above 1300° C. Finally, the result would be different if we postulate that the invaded formations, through the crushing incident to orogenic movement before the intrusion, had been heated above 200° C. Without here entering on the discussion of these further complications, we may conclude that probably from four to six volumes of the superheated primary basalt would furnish the heat-energy necessary for the solution of one volume of wall-rock.

If this rough estimate is even approximately correct, we have some idea of the actual assimilating power of plutonic magma which has been superheated a couple of hundred degrees. We also see a definite reason for the fact that post-Archean granites have never, so far as known, stoped their way to the earth's surface. The crust has been too thick, the expenditure of heat-energy in forming the syntectic magma too vast, that the process could operate to its extreme and so endanger the stability of the crust-roof above each batholith.

Objection founded on rarity of evidences of assimilation at observed wall-rocks.—One of the most commonly expressed objections to any theory of the replacement of invaded formations by batholithic magmas consists in emphasizing the obvious fact that the average xenolith and average wall-rock of batholiths do not show direct evidence of melting or of solution in the granitic magma. This objection has been answered by the writer in several publications* and also by Andrews in most vivid fashion.† The point has, however, been restated by several authorities without any adequate discussion of the subject. No one can deny that, when the magma is all but frozen, it is incapable of assimilating xenolith or wall-rock on any large scale. The practical question is as to the magma's efficiency during the long antecedent period of its history. It is true that bed-ridden centenarians did not build the pyramid of Cheops; it does not follow that men did not build it.

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* According to the stoping hypothesis almost all of the heat conducted into the shells of country-rock successively stoped away during the magmatic period, is not lost, but is available for the abyssal assimilation of the engulfed blocks. In view of the slowness with which the mixtures of powdered silicates melt, it is probable that notable exothermic reactions do not take place. The possibility of endothermic reactions seems to be a more open question.

If it be assumed that the quartz of granite has crystallized at or below 800° C.,‡ it follows that complete rigidity is not established in a granite batholith until it has cooled to at least 800° C. Down to about that temperature limit (of undercooling), therefore, magmatic stoping is still possible. The lowest limit of active assimilation cannot well be much below 1000° C., while the temperature required to melt the average xenolith is about 1200° C. As the viscosity of granitic magmas increases greatly below 1200° C., diffusion and convection must become rapidly inadequate to remove syntectic films at main contacts, so that the molecular lowering of the fusion-point will be confined, within the interval 1200°–800° C., chiefly to the sunken blocks. It follows, first, that in the very long period of time occupied in the cooling of a plutonic mass from 1200° C. to 800° C., there will be little or no melting or solution of wall-rock; secondly, that many shells of roof-rock, perhaps aggregating thousands of feet in thickness, may be stoped away during that same period of time. In other words, because the shatter-period is longer than the period of active assimilation at the roof, it is an essential feature of the stoping hypothesis that neither visible xenolith nor main wall of a granite batholith should normally show a collar of assimilation. So far from being a difficulty, the fact that this is generally true is a distinct argument in favor of the stoping hypothesis.

Abyssal assimilation.—In the first paper of this series the writer stated grounds on which one must believe in the complete solution of engulfed xenoliths. One has only to imagine a block of gneiss, say ten meters in diameter, sinking through a column of superheated basalt twenty or thirty kilometers deep, to become convinced of the ultimate fate of that block. If the somewhat cooled lavas described by Lacroix,* von John,† Dannenberg,‡ Sandberger§ and others could dissolve rock-inclusions in the notable way described by those authors, we must credit a vast solutional efficiency to plutonic magma when it attacks similar blocks in great depth. The lava has a few hours or days in which to do its work; the abyssal magma has centuries if not a large part of a geological period!

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* This Journal, xv, p. 281, 1903; Bull. Geol. Soc. of America, xvii, p. 372, 1906.

† Records, Geol. Surv. of N. S. Wales, viii, Pt. 1, p. 126, 1905.

‡ Cf. A. L. Day and E. S. Shepherd, Jour. Amer Chem. Soc., xxviii, p. 1099, 1906.

It must be remembered that geosynclinal sediments are rocks unusually rich in water, chlorides, sulphur trioxide, etc.; all substances aiding solution in the primary magma and in the secondary (syntectic) magma itself. It is probably also owing to these fluids in large part that granitic magmas have crystallized at comparatively low temperatures.

The conception of stoping with abyssal assimilation has many more points in its favor than can be cited for pure marginal assimilation. A few of the special grounds for preferring the newer to the older hypothesis may be noted.

First, marginal assimilation is largely effective only in the earliest part of the magma's history, when it is absolutely and relatively very hot. There is thus an early time-limit fixed for the gigantic work of dissolving the thousands of cubic kilometers actually replaced in the intrusion of a large batholith.

Secondly, the assimilation, on the older view, takes place primarily on main contacts and along a relatively limited amount of surface. For example, a cube of wall-rock one kilometer in diameter can offer only about 1,000,000 square meters of surface at a time to the dissolving magma. If that same cube were shattered into cubes 10 meters on the side and then engulfed, the magma would carry on the work of solution on 600,000,000 square meters of surface.

Thirdly, the average crust-rock being allied chemically to gneiss, is more soluble in basic magma than in acid. On the stoping hypothesis, solution of the xenolith generally occurs in the lower, basic part of the magmatic chamber; on the older view, it is granitic magma which must do most of the work of solution. For even if the originally injected magma is a basalt, the products of its assimilating activity, being more acid and less dense than itself, must remain at the batholithic roof and rapidly assume the chemical composition of mean mountain-rock. It follows that the primary magma must be enormously more superheated than is required on the stoping hypothesis or than seems easy of explanation, in view of the

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[*] Les Enclaves des Roches Volcaniques, Macon, 1893.
[†] Jahrb, d. k. k. Reichsanstalt, Vienna, lii, p. 141, 1902.
[‡] Tscherm. Min. u. Petrogr. Mitth., xiv, p. 17, 1895.
[§] Sitzungsber. K. Bair. Akad. Wiss., p. 172, 1872.

difficulty of understanding how plutonic magma, which is capable of intrusion, can become superheated more than two or three hundred degrees Centigrade.

Fourthly, the stoping hypothesis has the special advantage of providing a mechanism of thorough agitation within a batholith. Strong stirring of the mass is induced by the sinking of xenoliths and by the necessary rising of the magma locally acidified by their solution. This agitation can explain the marvelous homogeneity in each large batholith. It helps greatly to explain the manifest evidences of magmatic differentiation within batholiths—splittings and segregations that cannot be due to the slow process of molecular diffusion or to mere thermal convection. The whole process of stoping and the rising of syntectic magma tends to equalize the temperatures in the batholithic chamber and thereby we can understand the even grain and rapid, nearly simultaneous crystallization of a batholith throughout its visible depth.

Fifthly, the engulfment of blocks of geosynclinal sediments enriches all parts of the batholiths with water, chlorides, etc. which so greatly aid solution ; while, on the older view, these agents are confined to the uppermost part of the chamber.

Sixthly, as already noted, the cleansing of syntectic films from contact of solid and liquid is much the more rapid and perfect according to the stoping hypothesis, thus providing and renewing conditions for molecular lowering of the fusion-point along contacts.

In short, the newer view has the advantage of not only better explaining the facts of the field but it is incomparably more economical of the heat postulated for the work of batholithic replacement than is the theory of pure marginal assimilation. Melting and marginal assimilation of country-rock takes place in the initial, superheated condition of a basaltic injection, but must be regarded as always subordinate in replacement efficiency to stoping and abyssal assimilation.

Existence of basic stocks and batholiths.—Finally, the fact that some large bodies of plutonic rocks are basic has been advanced as an objection against the idea of stoping.* This fact early impressed itself on the present writer and led to his reviewing the geological literature to determine, if possible, the number, distribution, and age of these bodies. It was found that most of those which have undoubtedly batholithic development on a large scale are of pre-Cambrian age and are chiefly anorthosite intrusions. In this Journal, vol. xx, 1905, p. 216, the guarded suggestion was made that the anorthosites of Canada and the Adirondack Mountains are so basic because of the absorption of crystalline limestones. On more mature consideration this suggestion seems inadequate and a more general explanation must be sought.

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* W. Cross in Science, xxv, p. 620, 1907.

Adams describes the great anorthosite mass of Morin, Quebec, as genetically associated with an adjacent gabbro body of batholithic size.* The one is either a differentiate from the other or both are expressions of a common basic magma. The latter seems the more probable relation. In fact, both batholiths appear to represent the crystallized products of a magma allied to, if not identical with, the primary basaltic magma which has been the source of the heat in post-Archean batholithic intrusions.

The conditions of intrusion for these "upper Laurentian" masses seem to have differed from those typically represented in the post-Cambrian batholiths. The latter have been developed under heavy geosynclinal covers which have entailed considerable superheat in the basaltic substratum. It is not impossible that the "upper Laurentian" basic magmas, already cooled nearly to the solidification-point, were injected into the then thinner crust, or warped up with it, during crustal disturbance. Lacking superheat these magmas lacked stoping and assimilating power and, consequently, did not become acidified.

In favor of the conception that these magmas were near the solidification point at the time of their intrusion, is the fact that the anorthosites often show primary banding and are most extraordinarily granulated, as if by dynamic force which acted on the congealing mass near the close of the intrusion-period. Concerning the granulation Adams writes: "There are no lines of shearing with accompanying chemical changes, but a breaking up of the constituents throughout the whole mass, though in some places this has progressed much further than in others, unaccompanied by any alteration of augite or hypersthene to hornblende, or of plagioclase to saussurite; these minerals though prone to such alteration under pressure remaining quite unaltered, suffering merely a granulation with the arrangement of the granulated material in parallel strings. This process can be observed in all its stages, and there is reason to believe that it has been brought about by pressure acting on rocks when they were deeply buried and very hot. The anorthosite areas, of which there are about a dozen of great extent with many of smaller size, are distributed along the south and southeastern edge of the main Archean protaxis from Labrador to Lake Champlain, occupying in this way a position similar to that of volcanoes along the edge of our present continent." †

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* Canadian Record of Science, 1894–5.

† F. D. Adams, Jour. of Geol., i, p. 334, 1893.

Cushing and Kemp have published somewhat detailed accounts of the anorthosite forming a post-Grenville and pre-Cambrian batholith and its satellitic stocks in New York state.* The batholith covers about 3000 square kilometers in area. Cushing's petrographical descriptions show many points of agreement with Adams's description of the yet vaster Canadian batholiths. The anorthosite generally crystallized with exceptionally coarse grain and a porphyritic structure. Intense granulation is here again the rule, and from Cushing's published data it seems probable that the granulation followed hard after the act of intrusion. The characteristics and field-relations of the anorthosite are such as to suggest that they have resulted from abyssal injections of magma which was not superheated. A limited amount of stoping is possible in such a magma but extensive assimilation of country-rock is not possible for that magma.

Kemp has suggested that the New York anorthosite has, through fractional crystallization and the settlement of the basic minerals of early generation, been derived from a normal gabbro. † This idea may possibly explain the existence of the more pyroxenic contact-phase regularly occurring in the batholith. The contact rock is either gabbro or anorthosite-gabbro. It may represent the original magma but little affected by the settlement of the crystals of iron-ore, pyroxene and olivine. In the more slowly cooled interior of the mass their settlement could take place on a large scale.‡ In the Canadian batholiths this differentiation by fractional crystallization may have occurred just before the huge masses were injected into the crust.

The problem of the anorthosites is clearly as yet one for speculation rather than one capable of final solution. It seems proper to believe, however, that, since all or nearly all of the known anorthosite and gabbroid batholiths are of pre-Cambrian age, they owe their origin to special pre-Cambrian conditions. The stoping hypothesis as a whole expressly relates only to conditions which have characterized orogenic belts in post-Archean time.

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* H. P. Cushing, 18th Report of the State Geologist, Albany, p. 101, 1900; New York State Museum Bulletin No. 95, p. 305, 1905, and Bull. 115, p. 471, 1907. J. F. Kemp, 19th Ann. Report, U. S. Geol. Surv. pt. 3, p. 409, 1899.

† Op. cit., p. 417.

‡ Incidentally it may be remarked that the same conception might conceivably explain many internal basic contact-phases occurring in acid stocks and batholiths. This explanation is evidently opposed in principle to the prevailing view that the basic contact-shells are due either to diffusion of basic molecules toward cooling-surfaces, or to the combined influence of fractional crystallization and convection-currents in the magma. Neither of these hypotheses seems acceptable in the case of the anorthosite-gabbro batholiths, and the writer has come to question their validity as final explanations for some other types of intrusive bodies.

The gabbros of Paleozoic or later age represent bodies either too small or of too low temperature to carry on extensive stoping before their magmas became rigid. Diorite stocks and batholiths, according to the hypothesis, represent undifferentiated or but partially differentiated syntectic magma—of composition intermediate between rhyolite or granite and basalt. The average chemical analyses of the world's basalt, granite and diorite have been calculated by the writer from Osann's compilation.* It has been found that the diorite analysis is, oxide for oxide, almost the exact mean between the other two analyses.

These various considerations incline the writer to the view that the existence of a few large basic intrusions, cutting acid rocks, is not necessarily a fact fatal to the stoping hypothesis. Each of the cases needs special study, for they may shed much light on the difficult plutonic problem.

Differentiation of the syntectic magma.—In order to trace further the history of the engulfed xenoliths several principal conditions must be recognized. If the invading magma is superheated, so as to have the temperature of 1300° C., a block of heavy gneiss (sp. gr. at 20° C., 2·85) will speedily be heated to and above its own melting-point. While some of it is dissolved, much of it is converted into a molten globule of essentially pure gneiss. From Table II we see that the specific gravity of the globule would be about 2·40, while that of the surrounding primary magma would average about 2·72. This difference of density means that the globule must rise through the primary magma with a speed even greater than that with which the solid rock (specific gravity about 2·75) formerly sank.† As it rises the globule would wholly or partly mix with the primary magma. If wholly mixed the primary magma rapidly becomes a syntectic magma, approaching a diorite in composition. The molecular, syntectic film which is formed by solution along the surfaces of the block must, theoretically, contain equal parts of primary magma and xenolith material. If the former be basalt and the latter a granitoid gneiss, the film must have a dioritic composition. All three kinds of secondary magma—molten globules of gneiss, globule-material dissolved in primary magma as the globule rises, and the material formed in the molecular, syntectic film—must be considerably less dense than the primary basalt and rise toward the top of the batholith chamber. A net result of abyssal assimilation is a compound, secondary magma either dioritic or more acid than diorite.

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* Beiträge zur Chemischen Petrographie, II Teil ; Stuttgart, 1905.

† The same reasoning applies to xenoliths of normal gneiss immersed in acidified gabbro or diorite magma.

This reasoning is deductive but it can in some measure be checked by actual observations. Lacroix describes blocks of gneiss up to a cubic meter in size, which have been immersed in molten basalt. By the heat of the lava the blocks have been "entirely transformed" into porous glass.* Von John has described other examples of the same transformation.† The present writer has correlated a considerable number of instances where the gravitative stratification has certainly been produced in thick intrusive sheets.‡

A number of observers have come to the conclusion that the very act of the assimilation of acid material by basalt predisposes the magma to magmatic splitting. The fullest statement of this view is given by Loewinson-Lessing, in his remarkable "Studien über die Eruptivgesteine."§ There appears to be, as it were, a steady "antagonism" between the ferromagnesian and acid-alkaline elements in magmas. This primordial tendency toward immiscibility may well explain the dominant acidity and alkalinity of the pre-Cambrian terranes in every continent. From the earliest times the granito-rhyolite magma has tended to separate from the basaltic wherever the viscosity has been sufficiently low for such splitting. For similar reasons it appears that the syntectic magma of post-Archean batholiths only reaches a stable condition when it assumes the ancient relation. In the average case the fluidity has been high enough for the splitting. In some cases, however, it was so low that the undifferentiated syntectic has crystallized as diorite and allied rocks.

When the syntectic has differentiated, the process must be primarily controlled by density, so that the acid, generally granitic, product rises to the top of the chamber. There it may become locally further differentiated through fractional crystallization or other relatively subordinate process.

Without discussing the causes of differentiation in more detail, it suffices to point out, in summary, that magmatic stoping involves the placing of gravity at the head of the list of forces which produce the actual diversity among igneous rocks. In this the stoping hypothesis is believed to match the facts observed in experimental, industrial and geological studies of silicate melts.

Origin of granite; the petrogenic cycle.—The stoping hypothesis involves a more or less definite corollary relating

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* Les Enclaves des Roches Volcaniques, p. 563-5; Macon, 1892.

† Op. cit., p. 141.

‡ This Journal, xx, p. 185, 1905: also Festchrift zum siebzigsten Geburtstage von H. Rosenbusch, p. 203, Stuttgart, 1906.

§ Comptes Rendus, Congrès géol. internat, VII^e session, St. Petersburg, p. 375, 1899.

he Writer

to the genesis of granite as the staple visible material of post-Archean batholiths. Erosion has nowhere penetrated more than a few thousand meters in any of these batholiths. Considering the scale of operations, it follows that practically all post-Archean batholithic rock is of secondary origin. The field-relations show that the granite often replaces much geosynclinal sediment. Thick as many geosynclinal prisms are, however, it seems clear that another large, perhaps the larger, part of the replaced rock may be pre-Cambrian crystalline materials (averaging granitoid gneiss in chemical composition) which underlie geosynclinal areas, as they apparently underlie all the continental areas. The similarity of granites throughout the world may, indeed, be explained by the uniformity of the earth's primordial, acid shell and by the relative uniformity in average chemical composition of the greater geosynclinal prisms. Where sediments only are assimilated, the secondary granite may be of abnormal composition; this is the case with the granite of the Moyie Sill.*

The longer an abyssally injected and assimilating body holds its fluidity, the more perfect should be the gravitative differentiation. During this active stage lateral fissures or laccolithic spaces may be filled with offshoots of the slowly changing magma. In general these satellitic injections should succeed each other in the order of increasing acidity. In a fully represented petrogenic cycle at a batholithic area, then, the oldest intrusion should be a rock of gabbroid (basaltic) composition and the youngest an acid granite (chemically a rhyolite or quartz porphyry). Between these two an indefinite number of intermediate rock-types varying according to their degree and kind of differentiation from the syntectic—itself continuously varying in composition—might be represented in dikes or other satellitic forms. This further deduction from our hypothesis seems to be fairly matched by the observed order of igneous intrusions about the world's batholiths.†

Again, successive batholithic intrusions in the same area should show the same law of increasing acidity with decreasing age. If, for example, a crystallized granodiorite batholith be itself attacked by a later abyssal intrusive and in large part stoped away and remelted, the secondary magma collecting at the roof of the later batholith should be more acid than granodiorite. This would be expected because the mere act of remelting entails further gravitative differentiation. Each time that a silicate mass passes through the optimum temperature for magmatic splitting—probably an interval of one or two hundred degrees above its melting point*—the separation of its acid-alkaline and ferromagnesian elements by gravity is further perfected. Morozewicz has given a telling experimental demonstration of the process. He melted two pounds of granite and left the superheated melt in a hot part of an active glass-furnace for five days. It was then cooled to a glass. At the end of the time he found that the lower part of the melt carried 59·20 per cent of silica, the upper part 73·65 per cent; the original granite showed 68·9 per cent.† An actual case of repeated differentiation of the kind seems to be represented in the Okanagan Mountain range, where, one after another, the Osoyoos-Remmel, Similkameen and Cathedral batholiths have been intruded, and clearly in the order of decreasing specific gravity of the rocks.‡

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* This Journal, xx, p. 196, 1905.

† See first intrusion paper, p. 292.

It is, however, to be expected, on the stoping hypothesis, that the primary basaltic magma may close an entire petrogenic cycle, since the latest phase of a batholith, after crystallizing, may be fissured and injected with a small volume of the substratum. The common occurrence of diabase or prophyrite dikes in granite may be thus explained.

Origin of magmatic water and gases.—Finally, the stoping hypothesis implies that, since post-Archean batholiths have generally replaced large volumes of sediments, the volatile matter which is normally trapped within a geosynclinal prism should form an important part of the secondary magma.

An approximate idea of the amount of volatile matter in the average argillite§, sandstone and limestone of the world is readily obtained. For this purpose we may use Clarke's composite analyses of 843 limestones, 624 sandstones, 27 Mesozoic and Cenozoic shales and of 51 Paleozoic shales, together with 38 analyses of various argillites from different parts of the United States.‖ From these analyses the writer has determined, for the argillites, the average amount of water below 110° C. (H_2O-), water above 110° C. (H_2O+), carbon dioxide, carbon (and carbonaceous matter), and sulphur (in SO_3). These averages represent, respectively, 116, 116, 106, 78 and 78 typical specimens of argillite from as many localities. The averages for sandstone and limestone have been taken directly from Clarke's work and all three sets are noted in the following table:

An inspection of the table makes it clear that the total of the "combined water", carbon dioxide, carbon and carbonaceous matter, sulphur and chlorine in the stratified rocks

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* F. Loewinson-Lessing, op. cit., p. 380.

† Op. cit., p. 282. Cf. C. Doelter, Petrogenesis, Braunschweig, p. 79, 1906.

‡ Bull. Geol. Soc. America, xvii, p. 329, 1906.

§ The term "argillite" here includes both shales and slates.

‖ F. W. Clarke, Bull. No. 228, U. S. Geol. Surv., p. 20 ff., 1904.

TABLE IV.

	843 limestones	624 sandstones	116 argillites
H_2O-	·26%	·29%	1·25%
H_2O+	·73*	1·41	3·71
CO_2	38·03	2·64	2·45
C (including carbonaceous matter)	?	?	·81
S	·11	·03	·25
Cl	·01	trace	trace
Total	39·14	4·37	8·47

exposed in any geosynclinal prism must represent at least six per cent of the whole mass. It is highly probable that this minimum amount of volatile matter has similarly characterized such a series ever since the period in which the series was deposited.

No petrographer needs to be reminded that none of the commoner types of igneous rock contains anything like six per cent of original volatile matter. Nevertheless it is instructive to survey the facts actually visible in quantitative analyses of the igneous rocks. Water is the only volatile substance determined in igneous-rock analyses often enough to afford nearly reliable world-averages. From Osann's compilation the writer has deduced the average of H_2O- and H_2O+ for each of the following groups: 48 granites, 47 diorites, 12 gabbros, 24 basalts, 5 augite andesites and 11 rhyolites (Table V).

TABLE V.

	H_2O-	H_2O+
Granite	·17%	·64%
Diorite	·19	1·20
Gabbro	·26	1·35
Basalt	·73	1·03
Augite-andesite	·40	1·48
Rhyolite	·30	1·23

Clarke's averages for the volatile substances occurring in igneous rocks which have been analyzed according to approved methods are:

H_2O-	·40%
H_2O+	1·46
CO_2	·52
S	·11
Cl	·07
F	·02

Much of the combined water, probably all of the hygroscopic water, and most of the carbon dioxide of these analyzed igneous rocks are due to alteration or to absorption at the earth's surface. Allowing for that fact, it seems probable that none of the more widely distributed igneous rocks carries much more than one per cent of its own weight in volatile matter directly derived from the earth's interior.

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* Includes organic matter.

It follows that an enormous amount of water, carbon dioxide and carbon and sulphur compounds may be given off each time that geosynclinal sediments have been assimilated by molten and then crystallized magma. From each cubic kilometer of assimilated sediments about six per cent by weight of liquids and gases must be dissolved in the syntectic magma and, as crystallization proceeds, a large part of this fluid must be expelled.

In less important degree we may expect that the remelting or solution of an igneous rock by an intrusive magma should cause the evolution of some of the fluid matter which had been, as it were, frozen into the solid rock. Lincoln has aptly called such fluids "repressed emanations."* Gautier's and Brün's experiments show that many and probably all igneous rocks give off gases on being highly heated.† Reheating after cooling causes the renewed emanation of gases. Volatile matter trapped in crystallized secondary granite may thus be driven off, if that granite be dissolved in a younger molten magma with subsequent crystallization of the syntectic.

The stoping hypothesis in its broadest statement demands, therefore, that post-Archean, batholithic granites, syenites and diorites should be accompanied by special evidences of fluid emanations.

These fluids were deposited and buried in the strata. They have been resurrected in their activity. They have "risen again", both literally and figuratively; they may be called "resurgent" emanations. The "repressed" emanations of secondary igneous rocks may similarly be liberated by the distilling action of younger magma; as these fluids become revivified in their geological activities they may be regarded as forming a second kind of "resurgent" emanations. All "resurgent" emanations are of secondary origin and, therefore, stand in contrast to "juvenile" emanations, namely, those which, for the first time, have issued from the earth's interior and become geologically active on or near the surface. Magmatic emanations are, apparently, divisible into two great classes, both of which should be recognized in complete discussions of ore-deposits.

That the stoping hypothesis stands this further test seems to the writer entirely clear. The prevalence of quartz veins and pegmatites in the walls and roofs of actual granitic, syenitic, and dioritic stocks and batholiths, and the intensity of the contact-metamorphism produced by the intrusions of, and especially the emanations from, these rocks are facts as familiar as the comparative rarity of quartz-veins and pegmatites about gabbroid masses and the comparative feebleness of the contact-metamorphism produced by gabbros. The abundant water found in obsidian and rhyolite is, in this view, largely or wholly of secondary origin. Volcanic gases may similarly be largely "resurgent" rather than "juvenile." In no case, however, would one class of emanations be represented to the exclusion of the other. For post-Archean granites the emanations are dominantly "resurgent"; for gabbros the emanations are largely or dominantly "juvenile."

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* F. C. Lincoln, Economic Geology, ii, p. 268, 1907.

† A. Brun, Archives des Sciences Phys. et nat. Geneva, May and June, 1905 and November, 1906; A. Gautier, Annales des Mines (6), ix, p. 316, 1906, and Econ. Geol., i, p. 688, 1906.

Conclusion.—The first two papers of this series were written in the light of experimental results bearing on the methods of igneous intrusion. Since 1903 a number of additional leading experiments according to refined methods have been carried out by Doelter and his colleagues, by the Geophysical Laboratory staff at Washington, by Brun, Gautier, Hall, Douglas, Ladenburg and others. These later investigations, like those of Deville, Bischof, A. Becker, Lehmann, Fouqué, Michel Lévy, Cossa, Thoulet, Barus, Oetling, Hofman, Tammann, Morozewicz, Forbes, Joly, Mallet, Reade, Cusack, Weber, Åkerman, Vogt, Bartoli, Jamin, Lagorio, and others, seem to show that the physical conditions and processes involved in the stoping hypothesis have been in the main correctly stated.

It is obvious that further laboratory study of rocks on the physico-chemical side is highly desirable, but the accordance of independent experimental results now on record appears to have demonstrated: first, the enormous efficiency of thermal expansion in causing shattering stresses in solid rock; secondly, the fact that the average xenolith must sink in molten granite, syenite, diorite and acid gabbro when these magmas are under ordinary plutonic conditions; thirdly, that the sunken xenoliths must melt or become dissolved in the depths of plutonic magma, forming syntectic magma; and fourthly, that, if the primary magma is basic, the average syntectic must rise through it and thus collect at the top of the magmatic chamber.

The attempt has been made, in using the experimental results of Barus, Roberts-Austen and Rücker, Weber, Bartoli, Åkerman and Vogt, to estimate the amount of average crust-rock (gneiss) which may be dissolved in one volume of superheated primary magma (basalt). The sources of superheat in plutonic magma and a rough quantitative analysis of abyssal assimilation have been discussed. The result points to an explanation of the fact that magmatic stoping has not destroyed the roofs of post-Archean batholiths. The more general problem of the stability of batholithic covers which, on any theory of magmatic intrusion, seem to be in danger of foundering in the less dense magmas, is seen to have become less serious as that problem is viewed in the light of the new estimates of magmatic density. The possibility that some of the Archean batholiths were the scenes of actual, partial foundering of the earth's crust had been noted; the suggestion is made that, in late pre-Cambrian time, it had become thick and strong enough to inhibit extensive foundering of batholithic covers.

Various objections to the hypothesis seem to fall away so soon as they are confronted by the facts of experimental investigation on melted rocks and silicate mixtures. Other objections have been met by the facts derived from the field-work of many observers. The facts of field-occurrence and field-relations are opposed to the "laccolithic theory" and to that of marginal assimilation; on the other hand, these facts all seem to be explicable on the stoping hypothesis, which, therefore, is taken by the writer to afford the best working basis for the future investigation of granitic batholiths. In this conclusion the writer is in full agreement with Andrews and Barrell, two authorities who, with the intrusion-problem expressly in mind, have carefully scrutinized actual batholiths.

The hypothesis involves several important consequences, a few of which have been considered. If magmatic stoping and abyssal assimilation have largely operated during the intrusion of post-Archean batholiths and stocks, it follows that the material of these bodies is largely or wholly of secondary origin. In each case it is a differentiate from a syntectic magma formed by the solution of primary (acid) crust-rock or of geosynclinal sediments in the (probably basic) magma of the substratum. The order of eruption in batholithic areas, with respect to the acidity of the rocks, need not be absolutely fixed, but should show a strong tendency toward the succession of eruptives becoming more acid with decreasing age. Lastly, since most post-Archean granites have replaced large volumes of sedimentary rock, the suggestion seems warranted that the water and other volatile matters regularly given off in great volume from granitic magma, are also of secondary origin. Geosynclinal sediments are normally charged with relatively abundant fluids; it seems inevitable that these should, in part at least, be given off during the solution of wall-rock or engulfed xenoliths in an invading magma.

The principal field-relation on which the foregoing discussion hangs is the "replacement" of country-rock by magma in the intrusion of stock or batholith. Slow digestion and solution on main contacts has caused the replacement to a limited degree, but the facts of nature seem to enforce belief in the more rapid and more important mechanical replacement through magmatic stoping.

the Writer

With the Compliments of the Writer

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THE ORIGIN OF AUGITE ANDESITE AND OF RELATED ULTRA-BASIC ROCKS

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THE ORIGIN OF AUGITE ANDESITE AND OF RELATED ULTRA BASIC ROCKS

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INTRODUCTION

Petrographers are in general agreement as to the existence of many close mineralogical and chemical similarities between augite andesite and basalt. It has, in fact, been found to be impossible to draw any sharp line between the two species. Nevertheless, the olivine basalts, volumetrically the most important class of lavas on the globe, are distinctly characterized by the great abundance of the basic phenocrysts, augite and olivine with which basic plagioclase and much magnetite are regularly associated as minerals of early generation. The list of phenocrysts in augite andesite normally includes the pyroxene and an average plagioclase which is more acid than that in the olivine basalts; olivine is absent and magnetite is less abundant than in the basalt.

These relations suggest the hypothesis that the andesite has been differentiated from the basalt by a process of fractional crystallization. This hypothesis is, in principle, nothing new, but it seems never to have been applied in detail to this particular pair of rock-species.

Vélain's observations at the isle of Réunion led him virtually to state the hypothesis, but, at the time of the publication of his memoir, very little was known as to the actual temperatures of crystallization in lavas, as to the degrees of fluidity which the lavas exhibit at those temperatures, nor as to the density of molten lava, phenocryst, or remelted phenocryst. It was, therefore, impossible for Vélain to show the exact conditions under which fractional crystallization can produce an andesitic lava from an original basalt. The experimental studies of the last twenty years have now made it possible to discuss the process of differentiation somewhat more fully.

It is one purpose of this paper to offer a brief statement of the hypothesis as viewed in the light of the experiments of Doelter and others on the properties of lavas during crystallization. A second purpose is to lay emphasis on the enormous scale in which this particular kind of differentiation of lavas has taken place. It appears to be a world-wide phenomenon. Thirdly, the hypothesis necessarily involves the correlative derivation of certain ultra-basic lavas and rocks from olivine basalt. The conception has thus become of practical value to the writer in helping to explain the recurrent field-association of olivine basalt, augite andesite, and various peridotitic rocks discovered in the Selkirk, Columbia, and Cascade mountain-ranges of British Columbia. The hypothesis will here be presented in a general form, for, while it appears to explain the field-occurrences actually studied by the writer, the conception, like all petrogenic hypotheses, should stand the test of geological experience throughout the world.

TEMPERATURES AND ORDER OF CRYSTALLIZATION IN BASALT

As a result of numerous experiments on artificial basic melts and on natural lavas, as observed under the microscope, Doelter has proved that olivine, augite, magnetite, and plagioclase crystallize in the order which has been deduced from the microscopic study of basalt by Rosenbusch, Zirkel, and other systematic petrographers.[1]

According to Doelter, both magnetite and phenocrystic olivine crystallize from artificial basic melts at temperatures ranging between 1200° and 1030° C. The olivine largely crystallizes between 1200°

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[1] C. Doelter, "Die Silikatschmelzen," *Sitzungsberichte der k. Akad. d. Wissen.*, Vienna, Math.-naturw. Klasse, Bd. 103, 1904, p. 177.

and 1135° C.; the magnetite, largely between 1195° and 1100° C. The range for phenocrystic augite is 1190–960° C., with the most abundant crystallization between 1190° and 1100° C. The range for labradorite is 1125°–1075° C. He observed augite phenocrysts developed in molten basalt at the range, 1085°–920° C.; in molten limburgite at 1150°. Magnetite formed abundantly in molten basalt at 1095° C. and in molten limburgite at various temperatures ranging from 1170° to 1065° C. For rock-melts he records only one determination for olivine which "probably" crystallized out at 1085° C. in molten basalt.

Throughout most of the period of phenocrysitc development, that is, through a fall of temperature from 1200° to about 1080° C., basaltic lava is still notably fluid. Other experiments by Doelter have shown that strong fluidity characterizes various basic lavas at the following respective temperatures:

Etna basalt	1010° C.
Remagen basalt	1060
Vesuvian lava	1080
Limburgite	1050

It is fair to conclude that at the temperature of 1050° C. the average olivine basalt is fluid, and at 1100° C. quite thinly fluid. At the latter temperature its kinetic viscosity is probably comparable to that of the Hawaiian basaltic flow which Becker has calculated to have had, at the time of its emission, a viscosity about fifty times that of water.[1]

SINKING OF THE PHENOCRYSTS

In lava of such relatively high fluidity the olivine, augite, and magnetite crystals must slowly sink. Combining the results obtained by C. Barus[2] and, more recently, by J. A. Douglas,[3] on studies of volume changes as basic rock changes from the holocrystalline state to the glassy and then to the molten condition, the present writer has calculated that olivine basalt would have, at 1100° C. and at one atmosphere of pressure, a specific gravity averaging about 2.74; its groundmass, specific gravity ranging from 2.55 to 2.60. At the same temperature crystals of olivine (3.40), augite (3.30), magnetite (5.00), labradorite (2.70), and anorthite (2.75) would have specific gravities of, respectively, about 3.30, 3.20, 4.85, 2.61 and 2.66. These values are only approximate, but they show the order of the density differences to be expected between the phenocrysts and their mother-liquor. It appears probable that all the crystals except labradorite would slowly sink in the mother-liquor.

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[1] G. F. Becker, *Amer. Jour. of Sci.*, Vol. III, 1897, p. 29.

[2] *Bull. No. 103.*, U. S. Geological Survey, 1893.

[3] *Quart. Jour. Geol.*, Vol. LXIII, 1907, p. 145.

Some idea can be obtained of the rate at which the heavier phenocrysts would sink. For a spherical body the velocity of subsidence (x) at a time when steady motion is reached in a highly viscous fluid, may be found by solving the equation:

$$x=\frac{2g}{9}\times\frac{r^2(d-d')}{v},$$

where $g=$ the acceleration of gravity; r, the radius of the sphere; d, the density of the body; d', the density of the fluid; $v=$ viscosity.[1] This equation has been experimentally verified by Ladenburg who found that steel spheres, ranging from about 0.075 to about 0.2 cm. in radius took, respectively, from 570 seconds to 3,858 seconds to fall through a 20-centimeter column of Venetian turpentine—a substance a hundred thousand times more viscous than water.[2]

In an experiment by Jamin, pieces of stone sank through a layer of pitch in the course of several days (quelques jours), and corks simultaneously rose through the pitch, which, at 6° C, is much over 1,000,000,000,000 times as viscous as water.[3]

It is thus clear that even if the viscosity of the lava, within the temperature interval of early phenocrystic development, be many thousand times that of water, the phenocrysts must tend to sink. So long as such a crystallizing lava-column remains in its conduit and there undergoes cooling through the temperature interval, 1200°–1050° C.—a process necessarily involving a long period of time—the settling of the magnetite, olivine, and augite crystals will continue, though at a continuously slower rate. Theoretically the settlement will continue during the time occupied in the drop of temperature of another 100° C. or to the point when practical rigidity is established; but the rate of settlement must then be very considerably slower than in the interval, 1200°—1050° C. During the last-mentioned interval practically all of the olivine, much of the phenocrystic augite, and much of the magnetite of early generation has settled out of the upper part of the lava-column. Below 1050° C. the mother-liquor crystallizes. New crystals of magnetite and phenocrysts of augite and feldspar are formed but, because of the greatly increased viscosity, do not sensibly sink or rise in the freezing melt.

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[1] Cf. Poynting and Thomson, *Textbook of Physics, Properties of Matter.* (London, 1902), p. 222.

[2] R. Ladenburg, *Annalen der Physik*, Vol. XXII, 1907, p. 287.

[3] Jamin et Bouty, *Cours de Physique* (Paris, 1888), Tome 1. 2^e fascicule, 1888, p. 135.

To estimate the chemical composition of the mother-liquor it would be necessary to know the composition of the original basalt and the quantity and composition of each settled-out phenocrystic material. The problem may be solved through a careful quantitative chemical study of a typical olivine basalt; the results are of the same order as those obtained from a comparison between the average compositions of the world's olivine basalt and of its phenocrysts. The result of these comparisons will be detailed on a later page.

FORMATION OF ULTRA-BASIC MAGMAS AND OF AN ANDESITIC MOTHER-LIQUOR

As the phenocrysts sink they enter levels in the conduit where the temperature is higher than near the surface, and where the basalt is as yet completely molten. Probably the lava-column grows slightly more dense toward its base, according to faint chemical differences in the successive strata. The sunk phenocrysts, at the lower levels and higher temperatures will, in turn, become re-dissolved or melted. Deville,[1] Doelter[2] and others have shown that both olivine and augite expand extraordinarily in passing from the crystalline state to the glassy. The specific gravities of a few typical specimens at room temperatures are indicated in the following table:

	Crystal	Glass	Molten at 1200° C.
Augite (Doelter)	3.30	2.92	2.83
Augite (Deville)	3.267	2.803	2.72
Olivine (Deville)	3.381	2.831	2.75

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[1] Cf. F. Zirkel, *Lehrbuch der Petrographie* (Leipzig, 2d ed., 1893), Vol. I, p. 680.

[2] C. Doelter, *Physikalisch-chemische Mineralogie* (Leipzig, 1905), p. 8.

Each of these glasses would expand, with heating, at least as fast as diabase, e.g., 3 per cent. for 1200° C. (Barus). At 1200° C., therefore, the remelted crystals would have specific gravities at least as low as the values shown in the third column. The specific gravity of normal basalt at 1200° C. for a type which is holocrystalline at specific gravity of 3.00, is about 2.74; that for a type holocrystalline at 3.10 is about 2.83—both these values being calculated from the data of Barus and Douglas. There seems to be good reason to believe, therefore, that the remelted and more or less perfectly dissolved phenocrysts would not sink indefinitely deep in the lava column, but would come to rest, forming one or more ultra-basic layers in the conduit.

In an active volcano the time allowed for the growth and sinking of phenocrysts may be long enough for a complete differentiation, or it may suffice only to remove some of the olivine and magnetite from the cooling surface layer of the column, or it may be so short as to forbid the growth of phenocrysts in the vent. Eruption will necessarily arrest or greatly retard the process. Where the outflow is rapid and continuous the original olivine basalt appears at the earth's surface. There, of course, the rapid cooling generally prevents recognizable differentiation in the way possible, and, apparently necessary, in the vent itself when the basalt stands within it for a considerable time.

We have, then, to expect in nature a continuously graded series of lavas from pure olivine basalt, through olivine-free basalt, to those phases of the mother-liquor which must approximate a basic augite andesite and then an acid augite andesite. The last rock would thus represent the one phase, the more voluminous phase, of this kind of differentiation. In view of the notably uniform composition of olivine basalts throughout the world we must further expect, that, in all cases where the fractional crystallization has run a complete course, the more acid phase should be relatively uniform in chemical composition. Its phenocrysts form when the magma's viscosity is relatively high and sinking is very slow.

The other products of the differentiation must also show a very great variation in composition. According to the special thermal conditions and shape of each lava-column, the phenocrysts must sink to different depths, and be segregated or dissolved in highly different proportions in different levels of the lava-column. From the original olivine basalt many types of ultra-basic basaltic magma and of peridotitic magma might be developed in the same conduit. During energetic eruption or intrusion into the walls of the conduit these might become mixed with each other and the resulting rocks present just such great variation as is actually observed in the peridotite family. Many peridotites, the picrites, limburgites (magma basalts), and abnormally olivinitic basalts are, in this view, the rocks derived from the fractional crystallization of olivine basalt, while augite andesite represents the other pole of the differentiation.

TESTS OF THE HYPOTHESIS

1. *Chemical relations.*—The view that olivine basalt may be the parent of augite andesite and of several ultra-basic igneous types is well supported by a comparison of Streng's total analysis of a dolerite and his analysis of its own glassy base.[1] The two are here quoted.

	Dolerite	Glassy base
SO_2	49.08	55.15
TiO_2	1.82	2.05
Al_2O_3	13.43	15.37
Fe_2O_3	6.49	4.66
FeO	5.92	5.73
MgO	9.58	4.20
CaO	8.92	7.62
Na_2O	3.42	3.45
K_2O	1.00	0.74
H_2O	0.32	0.80
P_2O_5	0.51	
	100.49	99.77

The phenocrysts of the dolerite include andesine, augite, enstatite, and olivine; and magnetite is, of course, a noteworthy constituent. The composition of the glassy base clearly tends toward that of an augite andesite, though the whole possible amount of phenocrystic development was, in the case of this dolerite, not attained. Streng observed that the phenocrysts were largely or altogether wanting in the upper-surface layer of the dolerite flow, but he thought it "improbable" that their absence was due to settlement of the crystals. He attributed the phenomenon rather to the operation of Soret's principle, the flow having undergone true magmatic splitting under the influence of a maximum rate of cooling at the surface. As a result of the magmatic differentiation the lava crystallized differently near the surface and within the main body of the flow. To petrologists of the present day this view must seem highly improbable, as it involves an impossible speed of molecular diffusion. The alternative view, rejected by Streng, that the andesitic, phenocryst-free surface phase is due to settlement of the olivine and pyroxene, certainly seems more worthy of belief.

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[1] *Neues Jahr. für Min., etc.,* 1888(2), p. 211.

Secondly, the hypothesis of fractional crystallization might be tested by a comparison of the analyses of the world's average olivine basalt, augite andesite, and ultra-basic rocks, along with the average analysis of each of the staple phenocrysts in olivine basalt. An approximation to most of these averages has been made possible through Osann's great compilation of the rock-analyses made between the years 1884 and 1900.[1] From his tables an average of all the available typical analyses for each rock-species has been calculated by the present writer.

In Table I, Column 1, the average composition of 161 typical basalts (largely olivine-bearing), is entered. In Columns 2 to 6 are entered, in order, the average compositions of 11 Hawaiian basalts, 17 olivine diabases, 9 dolerites, 11 melaphyres, and 17 olivine gabbros. In Column 7 is entered the average of the 198 analyses which include all but the olivine gabbros. Since some of the basalts are olivine-free (perhaps through settling out of the phenocryst) it seems probable that the addition of the 17 olivine gabbro analyses to the average total would render it more nearly representative of the true world-average than that shown in Column 7.

Column 8 of Table II indicates the result of averaging all 215 analyses given in partial averages in Columns 1, 3, 4, 5 and 6, Table I, and hence represents rather closely the mean composition of olivine basalt throughout the world.

Column 9 gives the result of averaging 33 of the most typical augite andesites in Osann's compilation. Columns 10, 11, and 12 give the similar averages of, respectively, 49 peridotites, 7 limburgites and 3 picrites.

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[1] A. Osann, *Beiträge zur chemischen Petrographie*, Part 2, Stuttgart, 1905.

TABLE I

AVERAGE ANALYSES—BASALTS AND ALLIED ROCKS

	1 All Basalt	2 Hawaiian Basalt	3 Olivine Diabase	4 Dolerite	5 Melaphyre	6 Olivine Gabbro	7 First General Average
SiO_2	48.78	48.36	50.10	49.50	50.60	46.49	49.06
TiO_2	1.39	0.66	1.25	1.42	0.68	1.17	1.36
Al_2O_3	15.85	15.40	14.43	14.37	17.40	17.73	15.70
Fe_2O_3	5.37	6.48	5.06	6.55	4.57	3.66	5.38
FeO	6.34	10.07	6.31	5.84	6.29	6.17	6.37
MnO	0.29	0.80	0.25	0.17	0.46	0.17	0.31
MgO	6.03	4.19	7.32	7.75	4.89	8.86	6.17
CaO	8.91	8.69	9.53	9.96	8.09	11.48	8.95
Na_2O	3.18	3.34	2.75	2.50	3.23	2.16	3.11
K_2O	1.63	1.30	0.73	0.84	1.76	0.78	1.52
H_2O below 110° C	0.73	0.43	2.00	0.29	1.83	0.18	1.62
H_2O above 110° C	1.03			0.37		0.86	
P_2O_5	0.47	0.28	0.27	0.44	0.20	0.29	0.45
No. of analyses	161	11	17	9	11	17	198

Sum, 100.00 in each case.

Sum, 100.00 in all analyses.

TABLE II

AVERAGE AUGITE ANDESITE, OLIVINE BASALT, PERIDOTITE, LIMBURGITE AND PICRITE

	8 Second General Average Olivine Basalt	9 Augite Andesite	10 Peridotite	11 Limburgite	12 Picrite
SiO_2	48.84	57.50	44.39	41.69	43.24
TiO_2	1.35	0.79	0.88	0.67	.....
Al_2O_3	15.90	17.33	5.14	14.80	15.19
Fe_2O_3	5.23	3.78	3.88	15.04	8.62
FeO	6.30	3.62	6.70		7.89
MnO	.29	0.22	0.19	.....	....
MgO	6.38	2.86	29.17	8.64	8.56
CaO	9.15	5.83	6.31	11.98	13.78
Na_2O	3.05	3.53	0.64	3.52	0.54
K_2O	1.46	2.36	0.76	1.17	0.48
H_2O	1.60	1.88	1.80	2.36	1.21
P_2O_5	0.45	0.30	0.14	0.13	0.49
No. of analyses	215	33	49	7	3

Sum, 100.00 in each case.

All of these averages were made after the method of Washington and Clarke in their latest determinations of the average rock-analysis for the world. Thus, the average for each oxide is based only on the actual number of its determinations in the respective group; "trace" is taken to mean 0.01 per cent.

For the purpose of making a fair comparison among these averages it is necessary to recalculate them all as anhydrous; for, clearly, a large, though unknown, fraction of the water entered in the hundreds of analyses, must be regarded as mechanically absorbed water.

Table III, Columns 13, 14, 15, 16, and 17, shows these recalculated averages.

TABLE III

RECALCULATED AVERAGES, WATER EXCLUDED

	13 Olivine Basalt	14 Augite Andesite	15 Peridotite	16 Limburgite	17 Picrite
SiO_2	49.65	58.65	45.20	42.69	43.77
TiO_2	1.37	0.80	0.90	0.68	.....
Al_2O_3	16.16	17.67	5.25	15.18	15.37
Fe_2O_3	5.31	3.85	3.95	15.43	8.72
FeO	6.40	3.69	6.82		7.99
MnO	0.29	0.22	0.19	.....	.....
MgO	6.48	2.90	29.70	8.85	8.66
CaO	9.30	5.92	6.43	12.27	13.95
Na_2O	3.10	3.60	0.65	3.58	0.55
K_2O	1.48	2.40	0.77	1.19	0.49
P_2O_5	0.46	0.30	0.14	0.13	0.50

Sum, 100.00 in each case.

Table IV, Column 18, indicates the average composition of the olivine phenocrysts in basalt, according to Rammelsberg.[1] Column

TABLE IV

COMPOSITION OF PHENOCRYSTS IN OLIVINE BASALT

	18 Olivine (Rammelsberg)	19 Augite	20 Labradorite (Ab_1An_1)	21 Anorthite
SiO_2	41.01	47.72	55.55	43.16
TiO_2	.....	1.10	.....	.....
Al_2O_3	.....	6.31	28.35	36.72
Fe_2O_3	.....	3.12	.....	.....
FeO	9.83	5.31	.....	.....
MnO	.....	0.50	.....	.....
MgO	49.16	14.01	.....	.....
CaO	.....	20.71	10.36	20.12
Na_2O	.....	0.80	5.74	.....
K_2O	.....	0.42	.....	.....
Sp. gr. of crystal	ca. 3.40	ca. 3.30	2.700	2.75

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[1] Quoted in Zirkel's *Lehrbuch der Petrographie*, 2d ed. (1893), Vol. I, p. 353.

19 gives the result of averaging 14 analyses of augite phenocrysts from basalt, dolerite, limburgite, and labradorite porphyrite, as stated in the appendix to Osann's compilation. Columns 20 and 21 represent typical analyses of labradorite and anorthite respectively.

By the settling-out of olivine, augite, and magnetite the molten lava or mother-liquor, must, when compared with the original basalt, be poorer in iron oxides, magnesia and lime, and richer in silica, alumina and the alkalies. The change in alumina might be slight, provided that the anorthite phenocrysts also settled out. Crystals of labradorite and andesine would slowly rise and enrich the upper part of the lava-column with silica, alumina, and soda. Chemically the average augite andesite appears to correspond to the mother-liquor, possibly bearing up-floated plagioclase crystals, while many of the ultra-basic rocks, picrite, limburgite, dunite, harzburgite, and other peridotites, correspond to those magmatic types developed deep within the lava-column by the settling of the phenocrysts.

2. *Observed cases of sunken and risen phenocrysts.*—A few instances of gravity differentiation accompanying the growth of phenocrysts in magma have been observed in rocks and also in artificial melts. Both Scrope, in 1825, and Charles Darwin, in 1844, published hypotheses, now classic, of such fractional crystallization in nature. Clarence King, in 1878, adopted their conclusion and added new examples studied by him at Kilauea. He broke asunder some of the thin, tongue-like flows of once very fluid basalt and found that in every case the bottom of the flow was thickly crowded with triclinic feldspars and augites, while the whole upper part of the stream was of nearly pure isotropic and acid glass.[1] He further remarked on the general absence of phenocrysts in some of the great Hawaiian flows; the crystals sank away into the conduit before eruption. Certain other Hawaiian flows described by E. S. Dana show the complementary feature of being ultra-basic and crowded with olivine crystals, which make up as much as 50 per cent. of the rock.[2] Neither at Kilauea nor at Mauna Loa, however, would one expect to find a notable differentiation of augite andesite. The extreme fluidity of lava-columns in both of the great pits seems to indicate general tempera-

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[1] *U. S. Geol. Explor. 40th Parallel*, Sys. Geol., 1878, p. 716.

[2] J. D. Dana, *Characteristics of Volcanoes* (New York, 1891), p. 324.

tures above those at which even olivine can form. The "white" heat of the huge lava-fountains corresponds to a temperature of 1300° C. or over.[1] Granting that the Hawaiian conduits have always been so much superheated, it is not surprising that so few types of lava, other than olivine basalt, have been found on the island.

Iddings has described a striking case of the sinking of the augite phenocrysts, enriching a thick layer at the bottom of a 30-foot intrusive sheet on Electric Peak, Yellowstone Park.[2] It is not clear why so thin a sheet should have been differentiated and thus stand in contrast to hundreds of mapped sills of at least as great thickness, in which no differentiation is visible. Possibly the explanation is to be found in the fact that the Electric Peak sill is unusually rich in sulphur trioxide, chlorine, lithia, and "combined" water—substances which tend to lower the viscosity of magmas. In this case, though the magma was rather quickly chilled against the inclosing shales, the dissolved volatile matter maintained the fluidity long enough for the phenocrysts to fall to the bottom.

Against the hypothesis of fractional crystallization and gravitative sinking, it might be objected that the heavy minerals of early generation in gabbros and other plutonic types which have crystallized under slow-cooling conditions, are generally quite uniformly distributed through rock and show no concentration by gravity. There are, however, good reasons to believe that each plutonic magma, before any crystallization begins, is regularly cooled down several hundred degrees of the Centigrade scale below the melting-point of the rock resulting from the crystallization of the magma. The experiments of Oetling[3] and Amagat[4] show that pressure is a principal cause of this retardation of crystallization. According to Vélain[5] the retention of the volatile solvents, such as chlorides, would further tend to lower the temperature of crystallization in depth, while their escape at a volcanic vent would allow crystals to form at a higher temperature and therefore during a less viscous stage of the magma's history. In an under-cooled silicate melt crystals must sink but slowly.

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[1] Cf. H. Le Chatelier and O. Boudonard, High Temperature Measurements, trans. by G. Burgess, New York, 1904, p. 246.

[2] *Monograph* 32, Pt. 2, U. S. Geol. Surv., 1899, p. 82.

[3] *Tscher. min. u. petrog. Mitt.*, Vol. XVII, 1897, p. 332.

[4] *Comptes Rendus*, No. 16, 1893.

[5] *Op. cit.*, p. 181.

The crystallization of most plutonic magmas and of lavas at the earth's surface are thus believed to take place under strongly contrasted conditions. At the surface of a lava-column olivine, magnetite, augite, and plagioclase begin to form at high temperatures, when the viscosity is relatively low; the time-interval of crystallization for the whole magma is relatively long. Under plutonic conditions the same minerals crystallize at lower temperatures, when high viscosity is established and (because of under-cooling) the time-interval of crystallization is probably short.

Nevertheless, in some plutonic bodies of large size a certain amount of fractional crystallization and settlement of basic minerals may have actually taken place. Kemp has suggested that the anorthosites of the Adirondacks have been derived from more normal gabbro as a result of the sinking of the heavy constituents, either crystallized or still molten. He considers that the titaniferous magnetites of the region were erupted into the anorthosite after the anorthosite had consolidated, and implies that the molten ore has been derived from a *couche* which was formed from settled-out magnetite.[1] The relation of anorthosite and magnetite would, thus, be analogous to that postulated between augite andesite and certain olivine-rocks. Secondly, it is further possible that many basic contact-zones represent those parts of the respective intrusive masses where, on account of the relatively rapid cooling, the settling of basic minerals has been specially restrained, while the process has notably affected the composition of the slower-cooling interior of each mass. According to Kemp and Cushing[2] the huge anorthosite masses of the Adirondacks are characterized by wide contact-zones of rock relatively rich in pyroxene and magnetite (gabbro and anorthosite-gabbro). This gabbroid phase is usually finer grained and was presumably chilled more rapidly than the main body of the anorthosite.

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[1] *Nineteenth Annual Report*, U. S. Geological Survey, pt. 3, 1899, p. 417.

[2] H. P. Cushing, *Geology of Franklin County*, 18th Report of the State Geologist (Albany, 1900), p. 101; *New York State Museum Bull. No. 95* (1905), p. 305 and *Bull. 115* (1907), p. 471.

It is obvious that the gravity-separation of phenocrysts in lava which has once escaped from its conduit and then cooled rapidly, will not be conspicuous in the average flow. The separation will be most pronounced in the upper levels of an active volcanic neck or lava-filled fissure.

The rising of phenocrysts in magma more dense than themselves has seldom been actually observed, partly for the reason that few phenocrysts are lighter than their matrix. Mercalli has described a case of the concentration of leucite phenocrysts (sp. gr. at 1100° C. about 2.42) in the surface layer of an 1883 flow of Vesuvian lava (sp. gr. molten at 1100° C. about 2.70).[1] An analogous instance is recorded by Morozewicz who found that tridymite (sp. gr. at 1300° C. 2.24), derived from converted quartz grains, floated to the top of a crucible in which he had melted two pounds of granite (sp. gr. at 1300° C. about 2.40).[2]

3. *Andesite actually observed to have been derived from basalt at an active volcano.*—But all deductive argument for the hypothesis must, in order to be entirely convincing, be supplemented with the positive facts of the field. The great value of Vélain's discovery in the Île de la Réunion (Bourbon) has surely never been adequately recognized in discussions on the origin of magmas.[3] A few weeks before his party reached Réunion the 8000-foot volcano at the southeastern end of the island erupted fluid lava at its summit and, simultaneously, other lava issued from a fissure on the flank of the volcano, a fissure which communicated with the main vent.

The lava issuing at the summit was relatively acid and had a composition apparently similar to that of the lava collected at the summit in the walls of the crater itself. The latter was analyzed by Vélain, with the following result:

SiO_2	57.49	Na_2O	3.64
Al_2O_3	16.41	K_2O	2.92
FeO	10.65	Loss on ignition	0.13
MnO	0.06		
MgO	1.23		100.05
CaO	7.52	Sp. gr.	2.79

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[1] *Atti della Soc. ital. di scienze nat.*, Vol. XXVII, 1884.

[2] *Tscher. min. u. petrog. Mitt.*, Vol. XVIII, 1898, p. 332.

[3] C. Vélain, *Mission de l'île Saint-Paul* (Paris, 1888), pp. 101 ff.

This rock appeared to be quite holocrystalline and was essentially composed of feldspar microclites, augite and iron oxide; olivine was a rare accessory. The augite and feldspar appear in large part to have crystallized at the same time.

The lava from the flanking fissure was examined and found to be very dense (sp. gr. 2.97) and much more basic than the lavas at the edge of the crater "qui datent pourtant de la même phase éruptive." This basic lava carried only 48.98 per cent of silica. It is rich in olivine, magnetite and augite, with which less abundant crystals of anorthite are associated.

> Ainsi, déversement d'une lave vitreuse, relativement riche en silice, par-dessus les bords du cratère comme un trop-plein, puis soutirage par des crevasses latérales, ouvertes à une assez grande distance du sommet, d'une lava tout à la fois plus basique et plus dense, chargée de péridot, mais se rapprochant de la précédente par la nature de son élément feldspathique (anorthite),-tels sont les deux phénomènes consécutifs présentés par l'éruption de 1874. On peut les considérer comme représentant la marche habituelle des éruptions de ce volcan.[1]

The basic lava was observed to flow slowly, so that one may conclude that the temperature was well below 1200° C. or the point at which olivine begins to form in a cooling basalt. Other recorded flows of basaltic nature, such as that of 1812, ran with great speed, indicating higher temperatures and much lower kinetic viscosity. The temperature of the lavas within the vent is, thus, sufficiently variable to allow of their intermittent differentiation by the sinking of phenocrysts. In the process of time the island has been built up by alternating flows of olivine basalt, basic and acid augite andesites, and either true picritic rocks (described by Vélain) or their near relatives, ultrabasic basalts. Normal olivine basalt formed the original lava, whence, through fractional crystallization, the other types were derived.

4. *General field relations.*—The hypothesis implies that, in general, the derivation of augite andesite and olivine rocks from olivine basalt takes place in the relatively small openings represented by volcanic vents; secondly, that the effective differentiation occurs only when the lava column stands in the vent for a considerable time, and at temperatures ranging between 1200° and 1050° C.; thirdly, that the peri-

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[1] C. Vélain, *op. cit.*, p. 182

dotitic, limburgitic or picritic magma resulting from the remelting of the settled phenocrysts, would form at the base of the lava-column and would be considerably smaller in volume than the correlative andesite; fourthly, that the heavy, ultra-basic magma would oftener form intrusive than extrusive rocks, and would fill fissures either in the basal beds of the cone itself or in the older formations on which the cone rests; fifthly, that the primary basaltic magma is directly represented on the earth's surface where the lava was erupted rapidly in great volume, and at such temperatures that the phenocrysts of large size had not yet formed in abundance; and, sixthly, that augite andesite would be most often developed in and about the great volcanic cones, in the building of which the physical conditions and the duration of eruption were appropriate for pronounced fractional crystallization.

These various implications seem to be fairly matched by the facts of rock-distribution and rock-occurrence. The whole group of rocks here considered—basalts, andesites, peridotites, picrites, limburgites, etc., are consanguineous and several of them are commonly associated in the field. Where some of the derivatives are lacking in the existing outcrops, as in some of the British Columbia cases, the others may have been eroded away, or, on the other hand, have not yet been revealed by erosion. The ultrabasic rocks never form bodies of batholithic size but form dikes, sheets, "chonoliths,"[1] etc., and are thus always in such development as is explicable on this hypothesis. They form injected, not subjacent bodies. The olivine basalts are most largely developed in the vast lava-fields of the fissure-eruption type, where the emission of the primary lava has been too rapid for differentiation in the fissures. Augite andesite is most characteristically found in and about the greater cones, like those of the Andes mountain system or like most of the hundreds of very lofty cones rising from the floor of the deep sea. It has been already pointed out that the Hawaiian volcanoes carry superheated lavas, which, on account of the high temperature of the main body of each lava-column, cannot usually undergo pronounced fractional crystallization; yet the studies of J. D. and E. S. Dana show that some separation into olivine-free basalt and ultra-basic basalt has taken place before some of the eruptions. King's observations warrant the belief that some differentiation by fractional crystallization occurs in the lava after it escapes from the calderas of Hawaii. However, the Hawaiian rocks are more allied to those of an Idaho or Oregon lava-flood than to the typical andesites of Ecuador. The poverty of Etna lava in phenocrysts may be explained as due to the partial differentiation of the primary olivine basalt.[1]

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[1] *Journal of Geology*, Vol. XIII, 1905, p. 485 ff.

5. *Relation of augite andesite to other andesites.*—The hypothesis has been framed on the supposition that the primary basaltic magma has not been essentially affected by its solution or assimilation of chemically contrasted rock, material with which the lava makes contact as it rises or lies in the volcanic conduit. It is, however, most probable that the primary lava may in many cases absorb a certain amount of foreign material, either rock or fluid, and that the products of fractional crystallization must then vary notably from the few types so far mentioned. The process itself may be aided or retarded by such absorption, according as the absorption affects the temperatures of crystallization or the viscosity. Phenocrysts and ground-mass must change in chemical composition. Their separation by gravity would, then, produce magmatic materials not directly corresponding to augite andesite nor to any of the ultra-basic rocks formed directly from olivine basalt.

Hornblende andesites, mica andesites, dacites, etc., may, on this view, be derivatives of the primary basalt which has been modified by the assimilation of foreign rock-substance; while certain of the peridotites may represent some of the correlative differentiates of the compound lava. In a similar manner, one might possibly consider many lamprophyres and aplites as due to the analogous differentiation of their respective parent-magmas by the settling of basic minerals from the latter in its magmatic condition. It is not here the writer's purpose to discuss these possibilities in detail; they are noted rather to point to his belief that the commonly observed field associations and chemical relationships of augite andesite and other andesites are facts not opposed to the hypothesis outlined. It is, however, by no means intended to express the belief that *all* andesites or *all* peridotites have been formed through gravity separation of basic minerals; such a view is manifestly wrong.

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[1] Cf. H. Rosenbusch, *Mikros. Physiographie der massigen Gesteine*, 3d ed. (Leipzig, 1896), p. 1011.

6. *The rival hypothesis of magmatic differentiation.*—Finally, the hypothesis should meet the test of showing superiority over an obvious alternative suggestion. It might be conceived that augite andesite is due to the splitting of the basaltic magma before crystallization set in. In this view one must suppose that the splitting is due to a drastic change of physical conditions when the lava passes from abyssal levels to levels at or near the surface. The pressure is certainly very different in the two positions. However, no facts are in hand to show that a release of pressure causes immiscibility between two such magmas as molten andesite and molten peridotite, the two actually observed differentiates. If release of pressure alone caused the spontaneous splitting of olivine basalt into lighter andesite and heavier peridotite, we should very rarely expect to find true olivine basalt on the earth's surface, for most of these fluid lavas spend a considerable time in their conduits before being erupted. Against the idea is, further, the absence of any known physical reason why release of pressure should cause immiscibility. Experiments seem, on the contrary, to show that increase of pressure tends to promote immiscibility.

Immiscibility might conceivably ensue through a fall of temperature from a superheated condition, but there is no direct evidence that the phenomenon has a place in the history of volcanic cones or fissure-vents.

However probable may be the doctrine of immiscibility for certain magmas under plutonic conditions, we may regard the evidence on the problem as negative so far as volcanoes are concerned. The case may be summed up thus: The basaltic magma *may* split spontaneously into two or more magmas at a volcanic vent, but the phenocrysts of a molten basalt *must* sink while the lava undergoes the extremely slow cooling within the vent. Possibly both methods of differentiation are active. For the one advocated specially in this paper the physical conditions are quite simple and are largely understood quantitatively. The alternative view is at present a somewhat elusive conception for the petrologist and has few field-observations or compelling deductive considerations in its favor. It should, however, be added that the writer believes in magmatic splitting under other conditions than those at the crater of a basalt volcano. Either hypothesis will, of course, recognize augite andesite as a derivative from olivine basalt; the balance of probability is here attributed to the hypothesis of fractional crystallization.

SUMMARY AND CONCLUSION

The purpose of the writer has been to state the results of correlating many scattered items of fact derived from experimental and field studies. The correlation seems strongly to support the early views of Scrope, Darwin, and others as to the efficiency of fractional crystallization in the formation of igneous rocks. It is only quite recently that this general hypothesis could be put on a quantitative basis. Even now there are needed many additional physical and chemical determinations before the hypothesis can reach its full measure of conviction for the petrologist. Nevertheless a compilation of the already established facts seems to show that the idea of rock-differentiation by the gravitative separation of certain minerals gains greatly in meaning, force, and usefulness when applied to actual rock-types and to actual petrographical provinces.

The hypothesis explains the origin of a considerable number of igneous rock-types. Augite andesite and many olivine-free basalts form what may be called one pole of the differentiation of olivine basalt. Picrite, limburgite, many peridotites and other ultra-basic types form the other polar group of differentiates. The conditions for the differentiation in the typical and general case, involve, in each case, a somewhat prolonged residence of the primary basalt in a volcanic vent in which the temperature varies from about 1200° to about 1050° C. The phenocrysts formed in the lava at these temperatures, must slowly but surely sink. They then collect in the lower part of the lava-column. While still undissolved, they may be erupted along with the fluid lava in which they rest, giving ultra-basic porphyritic lavas; or, as seems more probable, they are slowly dissolved in this lower, hotter part of the lava-column, forming one or more ultra-basic layers which, on injection, crystallize into peridotites or, following extrusion, develop picritic or limburgitic rocks.

The hypothesis is backed up by a comparison of the average olivine basalt and average augite andesite of the world; by a comparison of the chemical nature of an individual and typical olivine basalt, its phenocrysts and its base; by the fortunate occurrence of simultaneous eruptions from the crater and low-lying lateral fissure at the Réunion volcano where Vélain shows the differentiation has taken place ideally; by the abundant proofs that heavy crystals do and must slowly sink and light crystals slowly rise in lavas, and in rock-melts; by the well-known facts of field-association and bodily development of augite andesite, olivine basalt and ultra-basic rocks throughout the different continents.

If the hypothesis correctly represents the facts and the augite andesites of the sea-floor volcanoes and of so many continental volcanoes are truly derivatives of olivine basalt, we have one more important link in the chain of argument leading to the belief that basaltic magma forms the universal substratum of the earth's crust today and has formed that substratum since Keewatin (early Archean) times. With this conception as a working theory the writer also connects the view that the crust overlying this basaltic substratum is stratified by density, so that the lower layer of the crust is crystallized basaltic magma (gabbro, possibly merging upward into anorthosite) and the upper layer is a composite of dominantly acid material. This latter is considered as made up largely of original granite or gneissic rock, similar to the staple fundamental gneiss of the pre-Cambrian—a layer probably less than thirty kilometers thick. This layer was crystallized in pre-Keewatin time; through it the basic Keewatin lavas were erupted; and through it basaltic magma has, from place to place and from time to time, ever since been erupted. The universal basaltic layer has thus been the effective source of the heat involved in the eruption of post-Keewatin igneous magmas. By the spontaneous differentiation of the primary basalt through fractional crystallization, the few rock-types specially discussed in this paper, have been locally derived. Most of the other eruptive rocks are, on this same working hypothesis, regarded as derived from the formation and differentiation of magmas which are the product of the solution of the acid, original gneissic shell and of its sedimentary veneer in the primary basalt. In other words, both the "syntectic"[1] (assimilation) theory and the fractional-crystallization theory seem to the writer to be essential and principal elements in the final solution of the genetic problem of the igneous rocks.

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[1] F. Loewinson-Lessing, *Congrès géol. internat. Compte rendu*, 7th session, St. Petersburg, 1897, p. 375.

With the Compliments of the Writer.

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AVERAGE CHEMICAL COMPOSITIONS OF IGNEOUS-ROCK TYPES.

By Reginald Aldworth Daly.

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By Reginald Aldworth Daly.

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Introduction: Purpose of the Paper.

The study of the igneous rocks has hitherto largely consisted in an analysis of their mineralogical and chemical composition, with the special intent to produce a satisfactory nomenclature and classification of the rocks as they occur throughout the world. This systematic petrography, though still pursued by a great number of workers, is now rivaled in interest and excelled in importance by its own offshoot, petrogeny. The science of the origin and history of the igneous rocks is reacting on the more purely descriptive subject, and at present petrologists are feeling their way toward a genetic classification of this great series of rock-types. Meantime, the much more numerous class of workers engaged on the problems of economic and general geology, of geochemistry and cosmogony, are raising highly important questions which belong to the field of petrogenesis. The problems thus raised are as fundamental as they are complex and difficult. For many of their solutions recourse must be had to the more modern geological reports and maps. With ever increasing skill and accuracy the distribution and relations of the rocks composing the earth's crust are being recorded by government officers and by geologists working in private capacity. For some thirty years past, as at present, the great body of geologists have mapped and described the igneous rocks in terms of what may be called the German system of nomenclature and definition. In particular, Rosenbusch's monumental treatises on the eruptive rocks have been, for a generation, the usual guide to the many authors who have described their findings among the igneous terranes of the world.

In view of these facts it is clear that a student in petrology who wishes to use the maps and memoirs should have a good conception of the rock-types recognized by Rosenbusch and by his hundreds of disciples among the field-geologists. It is true that in some details the usages of master and followers as regards names and classification have varied, but in a broad way Rosenbusch's definitions of the principal families and species of massive rocks have been used for maps and reports in all regions where modern work on igneous geology has been done. Just as the general sequence of the stratified rocks as first described in England, France, and Germany has been found to be closely paralleled in the rest of Europe and in the other continents, so the system of igneous rocks as at first developed from material largely collected in Europe has been nearly sufficient for the mapping of those rocks elsewhere. In the field as in the library the geologist soon learns that there is a persistent recurrence of types in the larger divisions of the earth's surface. The usefulness and objective character of Rosenbusch's classification are, therefore, proved by its adaptability in all the continents and islands.

Rosenbusch and his followers recognize some latitude of variation in the composition of each rock-type. The variation is both mineralogical and chemical, two rock specimens referred to a type showing differences in the proportions of the chemical elements found by analysis of the two rocks. In fact, no two analyses of granite, andesite, or any other one type have ever given precisely the same proportions of the dozen or more oxides which regularly make up an igneous rock. It is obvious that the student of map and memoir should, for many problems, have at hand the actual figures showing the most typical chemical composition of the rock-types to which his study is directed. In numerous cases an analysis of a single specimen is not so useful as that which could be made from a thorough mixture of specimens of the same rock-variety from all places on the globe where that variety occurs.

For obvious reasons such ideal analyses have never been made. In their stead the writer believes that the investigator of petrogenic and other world-problems may well use the averages calculated from the many excellent chemical analyses of rocks made since Rosenbusch's system of naming and classification has been in general use. It may, indeed, be argued that such averages would more nearly represent the chemistry of Rosenbusch's types than any of the respective single analysis which he has published in his treatise. These averages would be chemical "center-points" in his system of classification as *actually applied* to the terranes of the world.

So far as the writer is aware, the preparation of these averages has not hitherto been attempted to such an extent as to cover the chief families and species of igneous rocks. An approximation to the desired results is offered in the following tables.

The work of computing the averages has been lessened very greatly by the publication of Osann's "Beiträge zur chemischen Petrographie" (2nd part, Stuttgart, 1905). This remarkable book contains, in convenient arrangement, the statement of most of the eruptive-rock analyses (over 2400 in number) published in the interval between 1883 and 1901. The period of seventeen years lies within that during which systematic petrography has been dominated by Rosenbusch's names and definitions. In general, the number of analyses for each rock-species is so large that their average would be but slightly modified by the inclusion of the analyses made since 1900. In many cases, therefore, the extended labor required to search out from the literature the additional analyses, has not been considered necessary for the preparation of useful averages. For other averages it was necessary to include analyses published since 1900. The sources of such information are indicated below. Fortunately for the purpose, nearly the entire period since 1884 has seen the application of more or less refined methods of analysis; so that errors of observation for the leading oxides are relatively small.

METHOD OF CALCULATION.

The method of computation used is essentially like that employed by Washington and Clarke in their respective calculations of the "average composition" of all igneous rocks. In general, only the twelve more important oxides (including MnO) are recognized in the following tables. Distinctly "inferior" analyses were not considered. In each case the average was computed according to the actual numbers of determinations made by the analysts. Table I. shows these numbers for the respective rock-types, each column being headed by a key-number which corresponds with the named types of Table II. For some of the rocks BaO and SrO were computed. Their sum appears in the averages for CaO, as indicated in the tables. Similarly CO_2 and Cr_2O_3 were sometimes averaged and entered with H_2O and Fe_2O_3 respectively. As expected from the method employed, the average totals nearly always ran well over one hundred per cent. All averages were reduced to 100.00 per cent and entered in Table II. Each average analysis was then recalculated to 100.00 per cent after H_2O (and CO_2) had been subtracted. The results are also given in Table II., in which plutonics and corresponding effusives are grouped together. Magmatic relationships are often less obscured if these volatile oxides, which may be wholly or in part of exotic nature, are excluded. Finally, in order to facilitate reference to the tables, an index to the different rock-types was prepared and may be found below Table II.

It will be observed that certain rock-types have been omitted from the tables. The large class of "aschistic" dike-rocks is not represented because of their chemical similarity to the corresponding plutonic species. Other named varieties are omitted since their analyses are too few to give useful averages. In a few cases the mineralogical and chemical variations within each variety are so great that it has not seemed advisable to regard their averages as worthy of entry. Many other subordinate varieties of rock, though given special names, are chemically almost identical with the more important types entered in the tables and therefore have been excluded.

SOURCES OF INFORMATION.

The immediate sources of the analytical statements used in the computations are as follows: —

1. Beiträge zur chemischen Petrographie, zweiter Teil, by A. Osann. Stuttgart, 1905.
2. Chemical Analyses of Igneous Rocks published from 1884 to 1900, by H. S. Washington. Prof. Paper, No. 14, U. S. Geological Survey, 1903.
3. Elemente der Gesteinslehre, 2nd edition, by H. Rosenbusch. Stuttgart, 1901.
4. Lehrbuch der Petrographie, 2nd edition, by F. Zirkel. Leipzig, 1893.
5. Studien über die Granite von Schweden, by P. J. Holmquist. Bull. Geol. Institution, University of Upsala, Vol. 7, 1906, p. 76.
6. Some Lava Flows of the Western Slope of the Sierra Nevada, California, by F. L. Ransome. Amer. Jour. Science, Vol. 5, 1898, p. 355.
7. Matériaux pour la Minéralogie de Madagascar. Nouv. Archives du Muséum, (4), Vol. 5, Paris, 1903.
8. Geology of the Yellowstone National Park, by A. Hague and others. Petrography by J. P. Iddings. Monograph No. 32, Part. 2, U. S. Geological Survey, 1899.

9. Analyses of Rocks from the Laboratory of the United States Geological Survey, 1880 to 1903, by F. W. Clarke. Bulletin 228 of the Survey, 1904.
10. Geological and Petrographical Studies of the Sudbury Nickel District, by T. L. Walker, Quart. Jour. Geol. Soc., Vol. 53, 1897, p. 40.
11. Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana, by L. V. Pirsson. Bull. 237, U. S. Geological Survey, 1905.
12. Geology of the North American Cordillera at the Forty-ninth Parallel, by R. A. Daly (forthcoming; analyses by M. F. Connor and M. Dittrich used in calculating some averages).

The sources of the analyses used in each average are indicated by the authors' names at the head of the corresponding columns in Table II.

TABLE I.

SHOWING THE NUMBER OF SEPARATE DETERMINATIONS USED IN COMPUTING THE AVERAGE QUANTITY OF EACH OXIDE IN EACH ROCK-TYPE.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	47	114	184	236	64	24	40	50	7	5	8	23	50	48	7	13
TiO_2	22	74	60	87	40	10	30	20	5	4	5	14	35	26	6	5
Al_2O_3	47	114	180	232	63	23	40	49	7	5	8	23	49	48	7	13
Fe_2O_3	35	101	118	158	61	22	39	32	4	5	3	15	43	38	7	10
FeO	35	101	118	158	42	6	36	32	4	5	3	14	43	38	6	10
MnO	24	86	64	93	32	4	28	20	4	5	5	14	38	34	1	6
MgO	47	114	184	236	63	24	39	49	6	5	8	22	50	48	7	13
CaO	47	114	184	236	64	24	40	49	6	5	8	22	50	48	6	13
Na_2O	47	108	182	234	63	24	39	49	6	5	8	22	50	48	7	13
K_2O	47	108	182	234	63	24	39	49	6	5	8	21	50	48	7	13
H_2O	38	40	41	41	17	15	17	39	7	3	8	21	41	44	7	10
P_2O_5	15	34	73	81	27	4	23	17	3	3	..	7	34	25	4	4
BaO	8	..	35	35	..	..	..	..	..	..	..	..	..	..	..	..
SrO	5	..	21	21	..	..	..	..	..	..	..	..	..	..	..	..
	17	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
SiO_2	3	7	12	10	10	3	3	43	25	4	8	12	30	20	89	70
TiO_2	..	..	10	10	4	..	3	30	16	..	3	12	15	16	71	57
Al_2O_3	3	7	12	10	10	3	3	43	25	4	8	12	30	20	89	70
Fe_2O_3	3	7	12	10	6	3	3	30	18	2	2	12	24	18	86	69
FeO	2		12	10	6	3	2	30	18	2	2	12	24	18	86	69
MnO	..	..	10	10	4	3	2	30	15	1	3	12	14	11	66	53
MgO	3	7	12	10	10	3	3	41	25	4	8	12	30	20	89	70
CaO	3	7	12	10	10	3	3	43	25	4	8	12	30	20	89	70
Na_2O	3	7	12	10	10	3	3	43	25	4	8	12	30	20	85	67
K_2O	3	7	12	10	10	3	3	43	25	4	8	12	30	20	85	67
H_2O	3	7	9	10	10	3	1	26	23	4	6	12	30	17	47	36
P_2O_5	1	..	12	10	4	..	3	14	15	..	1	12	15	15	71	57

TABLE I.— *Continued.*

	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
SiO_2	87	33	20	24	10	7	41	198	161	20	17	11	9	24	17	5
TiO_2	51	16	13	13	9	6	26	132	113	13	6	5	8	16	10	4
Al_2O_3	87	33	20	24	10	6	41	197	160	20	17	11	9	24	17	4
Fe_2O_3	71	25	18	18	10	7	36	174	146	18	14	5	9	21	15	5
FeO	71	25	18	18	10	7	36	173	146	18	14	5	8	21	15	5
MnO	44	16	14	8	6	6	28	108	96	13	6	2	4	15	13	4
MgO	87	33	20	24	10	7	40	197	160	20	17	11	9	24	16	5
CaO	87	33	20	24	10	7	41	198	161	20	17	11	9	24	17	5
Na_2O	84	32	20	22	10	7	40	190	154	20	16	11	9	24	16	5
K_2O	84	32	20	22	10	7	39	190	154	20	16	11	9	23	16	5
H_2O	57	5	18	24	10	6	17	55	27	16	1	5	2	12	5	4
P_2O_5	47	14	13	11	9	6	27	135	116	14	6	4	9	16	11	4

	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
SiO_2	2	12	4	4	3	4	3	4	49	3	11	4	7	6	6	6
TiO_2	2	4	1	4	3	..	..	2	27	..	11	2	3	3	2	6
Al_2O_3	2	12	4	4	3	4	2	4	49	3	11	4	7	6	6	6
Fe_2O_3	2	10	4	4	3	1	2	4	40	3	10	2	2	5	6	6
FeO	2	10	4	4	3	1	3	4	40	3	10	4	2	5	6	6
MnO	2	3	4	4	3	1	1	3	32	..	6	..	..	..	4	4
MgO	2	12	4	4	3	4	3	4	47	3	11	4	7	6	6	6
CaO	2	12	4	4	3	4	1	4	49	3	11	4	7	6	6	6
Na_2O	2	12	3	2	3	..	1	4	31	3	11	4	7	6	6	6
K_2O	2	12	2	1	3	..	..	4	31	3	11	4	7	6	6	6
H_2O	2	7	4	4	3	4	3	3	47	3	10	2	7	4	6	6
P_2O_5	2	1	1	4	3	..	1	2	25	3	11	2	2	2	2	6

TABLE I.— *Continued.*

	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
SiO_2	24	20	4	20	16	4	1	2	7	7	5	9	26	3	10	4	10
TiO_2	8	14	4	4	11	3	1	2	2	6	5	3	23	3	10	4	9
Al_2O_3	24	20	4	20	16	4	1	2	7	7	5	9	26	3	10	4	10
Fe_2O_3	22	19	3	19	15	4	1	2	4	5	5	3	25	3	10	4	10
FeO	22	19	3	19	15	4	1	2	4	5	5	3	25	3	10	4	10
MnO	14	7	1	13	5	2	1	2	1	4	5	4	15	3	10	1	10
MgO	24	20	4	20	16	4	1	2	7	7	5	9	26	3	10	4	10
CaO	24	20	4	20	16	4	1	2	7	7	5	9	26	3	10	4	10
Na_2O	24	20	4	20	16	4	1	2	7	7	5	9	26	3	10	4	10
K_2O	24	20	4	20	16	4	1	2	7	7	5	9	26	3	10	4	10
H_2O	9	18	3	6	15	3	1	2	3	4	4	5	25	3	10	4	10
P_2O_5	19	9	3	16	8	1	1	2	5	2	4	6	23	3	10	4	9

	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
SiO_2	11	4	8	5	2	6	15	5	5	8	15	10	20	4	15	16	6
TiO_2	11	4	8	5	2	6	9	2	3	7	9	8	16	4	10	12	5
Al_2O_3	11	4	8	5	2	6	15	5	5	8	15	10	19	4	15	16	6
Fe_2O_3	11	4	8	5	2	6	11	2	4	8	10	8	16	4	10	14	5
FeO	11	4	8	5	2	6	10	2	3	8	9	8	16	4	10	14	5
MnO	11	4	8	5	2	..	8	1	4	8	9	7	17	1	8	9	2
MgO	11	4	8	5	2	6	15	4	5	8	15	10	20	4	15	16	6
CaO	11	4	8	5	2	6	15	5	5	8	15	10	20	4	15	16	6
Na_2O	11	4	8	5	2	6	15	5	5	8	15	10	20	4	15	15	5
K_2O	11	4	8	5	2	6	15	5	5	8	15	10	20	4	15	15	5
H_2O	6	4	8	5	2	6	11	2	3	7	10	10	19	4	10	16	3
P_2O_5	8	4	8	5	2	5	7	..	..	7	5	7	18	4	6	11	3

TABLE II.

SHOWING THE AVERAGE COMPOSITIONS CALCULATED FOR THE PRINCIPAL IGNEOUS-ROCK TYPES.

GROUP I.

	PLUTONICS.				EFFUSIVES.			
	1	2	3	4	5	6	7	8
	Pre-Cambrian Granites, including 16 Analyses of Swedish Types (Osann).	Pre-Cambrian Granites of Sweden (Holmquist).	Granites younger than the Pre-Cambrian (Osann and Clarke).	Granite of all Periods (Osann and Clarke).	Liparite, including 40 Rhyolites (Osann).	Liparites, as named by authors (Osann).	Rhyolites, as named by authors (Osann).	Quartz Porphyry (Osann).
No. of Analyses.	47	114	184	236	64	24	40	50
SiO_2	71.06	69.81	69.73	69.92	72.60	72.90	72.62	72.36
TiO_2	.48	.54	.34	.39	.30	.48	.25	.33
Al_2O_3	14.10	13.76	14.98	14.78	13.88	14.18	13.77	14.17
Fe_2O_3	1.46	2.17	1.62	1.62	1.43	1.65	1.29	1.55
FeO	1.63	1.87	1.66	1.67	.82	.31	.90	1.01
MnO	.18	.26	.11	.13	.12	.13	.12	.09
MgO	.59	.84	1.08	.97	.38	.40	.38	.52
CaO	1.97[1]	2.20	2.20[2]	2.15[3]	1.32	1.13	1.43	1.38
Na_2O	3.24	3.17	3.28	3.28	3.54	3.54	3.55	2.85
K_2O	4.50	4.38	3.95	4.07	4.03	3.94	4.09	4.56
H_2O	.69	.74	.78	.78	1.52	1.33	1.53	1.09
P_2O_5	.10	.26	.27	.24	.06	.01	.07	.09
Calculated as Water-free.								
SiO_2	71.56	70.33	70.28	70.47	73.72	73.89	73.75	73.16
TiO_2	.48	.54	.34	.39	.30	.49	.25	.33
Al_2O_3	14.20	13.86	15.10	14.90	14.10	14.37	13.99	14.33
Fe_2O_3	1.47	2.19	1.63	1.63	1.45	1.67	1.31	1.57
FeO	1.65	1.89	1.67	1.68	.83	.31	.91	1.02
MnO	.18	.26	.11	.13	.12	.13	.12	.09
MgO	.59	.85	1.09	.98	.40	.41	.39	.53
CaO	1.98[1]	2.22	2.22[2]	2.17[3]	1.34	1.14	1.45	1.39
Na_2O	3.26	3.19	3.31	3.31	3.59	3.59	3.60	2.88
K_2O	4.53	4.41	3.98	4.10	4.09	3.99	4.16	4.61
P_2O_5	.10	.26	.27	.24	.06	.01	.07	.09
Each sum = 100.00.								

[1] Includes .08% BaO and .01% SrO.

[2] Includes .06% BaO and .02% SrO.

[3] Includes .06% BaO and .02% SrO.

GROUP II.

	PLUTONICS.					EFFUSIVES.		
	9	10	11	12	13	14	15	16
	Nordmarkite (Osann and Washington).	Pulaskite (Osann and Washington).	Akerite (Osann and Washington).	Average Alkaline Syenite, including 7 Nordmarkites, 5 Pulaskites, 9 Akerites, and 3 Laurvikites.	All Syenite, including five Types of "Alkaline" Syenite.	Trachyte (Osann and Rosenbusch).	Keratophyre (Osann and Washington).	Quartz Keratophyre (Rosenbusch).
No. of Analyses.	7	5	8	23	50	48	7	13
SiO_2	64.36	61.86	61.96	61.99	60.19	60.68	61.51	75.45
TiO_2	.45	.15	.99	.56	.67	.38	.45	.17
Al_2O_3	16.81	19.07	17.07	17.93	16.28	17.74	17.37	13.11
Fe_2O_3	1.08	2.65	2.35	2.22	2.74	2.64	1.92	1.14
FeO	2.71	1.49	3.37	2.29	3.28	2.62	3.35	.66
MnO	.15	.01	.09	.08	.14	.06	.01	.29
MgO	.72	.55	1.38	.96	2.49	1.12	1.26	34
CaO	1.55	1.47	3.41	2.55	4.30	3.09	1.08	.83
Na_2O	5.76	6.45	4.65	5.54	3.98	4.43	5.23	5.88
K_2O	5.62	5.75	3.80	4.98	4.49	5.74	5.29	1.26
H_2O	.70	.47	.93	.76	1.16	1.26	2.45	.69
P_2O_5	09	.08	....	.14	.28	.24	.08	.18
Calculated as Water-free.								
SiO_2	64.81	62.15	62.55	62.46	60.90	61.46	63.06	75.98
TiO_2	.45	.15	1.00	.56	.68	.38	.46	.17
Al_2O_3	16.93	19.16	17.23	18.07	16.47	17.97	17.81	13.20
Fe_2O_3	1.09	2.66	2.37	2.24	2.77	2.67	1.97	1.15
FeO	2.73	1.50	3.40	2.31	3.32	2.66	3.43	.66
MnO	.15	.01	.09	.08	.14	.06	.01	.29
MgO	.73	.55	1.39	.97	2.52	1.13	1.29	.34
CaO	1.56	1.48	3.44	2.57	4.35	3.13	1.11	.84
Na_2O	5.80	6.48	4.69	5.58	4.03	4.49	5.36	5.92
K_2O	5.66	5.78	3.84	5.02	4.54	5.81	5.42	1.27
P_2O_5	.09	.08	....	.14	.28	.24	.08	.18
Each sum = 100.00.								

GROUP III.

	Plutonic.	Effusive.	Plutonic.	Effusive.
	17	18	19	20
	Laurvikite (Osann).	Rhomb-porphyry (Washington).	Monzonite (Osann and Washington).	Latite (Ransome and Daly).
No. of Analyses.	3	7	12	10
SiO_2	57.45	57.45	55.25	57.65
TiO_2	....	....	.60	1.00
Al_2O_3	21.11	19.53	16.53	16.68
Fe_2O_3	2.89	6.47	3.03	2.29
FeO	2.39		4.37	4.07
MnO	....	....	.15	.10
MgO	1.06	1.28	4.20	3.22
CaO	4.10	3.11	7.19	5.74[1]
Na_2O	5.89	6.35	3.48	3.59
K_2O	3.87	4.46	4.11	4.39
H_2O	.70	1.35	.66	.91[2]
P_2O_5	.54	....	.43	.36
Calculated as Water-free.				
SiO_2	57.85	58.24	55.62	58.18
TiO_2	....	....	.60	1.01
Al_2O_3	21.26	19.79	16.64	16.84
Fe_2O_3	2.91	6.56	3.05	2.31
FeO	2.41		4.40	4.11
MnO	....	....	.15	.10
MgO	1.07	1.30	4.23	3.25
CaO	4.13	3.15	7.24	5.79[1]
Na_2O	5.93	6.44	3.50	3.62
K_2O	3.90	4.52	4.14	4.43
P_2O_5	.54	....	.43	.36
Each sum = 100.00.				

[1] Includes .16% BaO and .07% SrO.

[2] Includes .14% CO_2.

GROUP IV.

	Plutonics.				Effusives.		
	21	22	23	24	25	26	27
	Foyaite (Osann and Rosenbusch).	Urtite (Osann).	Laurdalite (Osann).	Nephelite syenite (Osann).	Phonolite (Osann, Clarke, and Lacroix).	Leucite Phonolite (Osann and Washington).	Leucitophyre (Washington and Rosenbusch).
No. of Analyses.	10	3	3	43	25	4	8
SiO_2	56.11	45.61	54.36	54.63	57.45	54.89	49.83
TiO_2	.45	....	1.30	.86	.41	....	.71
Al_2O_3	21.33	27.76	19.99	19.89	20.60	21.28	19.00
Fe_2O_3	1.87	3.67	2.79	3.37	2.35	3.04	3.17
FeO	1.47	.50	2.58	2.20	1.03	1.49	3.59
MnO	.05	.15	.18	.35	.13	.01	.17
MgO	.55	.19	1.72	.87	.30	.66	1.79
CaO	1.72	1.73	2.96	2.51	1.50	2.31	5.69
Na_2O	8.48	16.25	8.28	8.26	8.84	5.62	7.19
K_2O	6.46	3.72	4.98	5.46	5.23	8.39	6.15
H_2O	1.50	.42	.22	1.35	2.04	2.31	1.93
P_2O_5	.01	....	.64	.25	.12	....	.78
Calculated as Water-free.							
SiO_2	56.96	45.80	54.48	55.38	58.65	56.19	50.82
TiO_2	.46	....	1.30	.87	.42	....	.72
Al_2O_3	21.65	27.88	20.03	20.16	21.03	21.78	19.38
Fe_2O_3	1.90	3.68	2.80	3.42	2.40	3.11	3.23
FeO	1.49	.50	2.59	2.23	1.05	1.53	3.66
MnO	.05	.15	.18	.35	.13	.01	.17
MgO	.56	.19	1.72	.88	.31	.68	1.83
CaO	1.75	1.74	2.97	2.54	1.53	2.36	5.80
Na_2O	8.61	16.32	8.30	8.38	9.02	5.75	7.33
K_2O	6.56	3.74	4.99	5.54	5.34	8.59	6.27
P_2O_5	.01	....	.64	.25	.12	....	.79
Each sum = 100.00.							

GROUP V.

	Pl.	Ef.	Plutonics			Effusives.				
	28	29	30	31	32	33	34	35	36	37
	Granodiorite (Osann and Clarke).	Dacite (Osann and Rosenbusch).	Quartz Diorite (Osann and Washington).	Diorite, includ'g Quartz Diorite (Osann).	Diorite, exclud'g Quartz Diorite (Osann).	All Andesite (Osann).	Augite Andesite (Osann).	Hypersthene Andesite (Osann).	Hornblende (Amphibole) Andesite (Osann).	Mica Andesite (Osann).
No. of Analyses.	12	30	20	89	70	87	33	20	24	10
SiO_2	65.10	66.91	59.47	58.38	56.77	59.59	57.50	59.48	61.12	62.25
TiO_2	.54	.33	.64	.80	.84	.77	.79	.48	.42	1.65
Al_2O_3	15.82	16.62	16.52	16.28	16.67	17.31	17.33	17.38	17.65	16.10
Fe_2O_3	1.64	2.44	2.63	2.98	3.16	3.33	3.78	2.96	2.89	3.62
FeO	2.66	1.33	4.11	4.11	4.40	3.13	3.62	3.67	2.40	2.20
MnO	.05	.04	.08	.13	.13	.18	.22	.15	.15	.21
MgO	2.17	1.22	3.75	3.88	4.17	2.75	2.86	3.28	2.44	2.03
CaO	4.66	3.27	6.24	6.38	6.74	5.80	5.83	6.61	5.80	4.05
Na_2O	3.82	4.13	2.98	3.34	3.39	3.58	3.53	3.41	3.83	3.55
K_2O	2.29	2.50	1.93	2.09	2.12	2.04	2.36	1.64	1.72	2.44
H_2O	1.09	1.13	1.39	1.37	1.36	1.26	1.88	.74	1.43	1.50
P_2O_5	.16	.08	.26	.26	.25	.26	.30	.20	.15	.40
Calculated as Water-free.										
SiO_2	65.82	67.67	60.31	59.19	57.56	60.35	58.65	59.92	62.01	63.20
TiO_2	.55	.33	.65	.81	.85	.78	.80	.48	.43	1.67
Al_2O_3	15.99	16.81	16.75	16.51	16.90	17.54	17.67	17.51	17.91	16.35
Fe_2O_3	1.66	2.47	2.67	3.02	3.20	3.37	3.85	2.98	2.93	3.67
FeO	2.69	1.35	4.17	4.17	4.46	3.17	3.69	3.70	2.44	2.23
MnO	.05	.04	.08	.13	.13	.18	.22	.15	.15	.21
MgO	2.19	1.23	3.80	3.93	4.23	2.78	2.90	3.31	2.48	2.06
CaO	4.71	3.31	6.33	6.47	6.83	5.87	5.92	6.66	5.88	4.11
Na_2O	3.86	4.18	3.02	3.39	3.44	3.63	3.60	3.44	3.88	3.61
K_2O	2.32	2.53	1.96	2.12	2.15	2.07	2.40	1.65	1.74	2.48
P_2O_5	.16	.08	.26	.26	.25	.26	.30	.20	.15	.41
Each sum = 100.00.										

GROUP VI.

	PLUTONICS.		EFFUSIVES.					
	38	39	40	41	42	43	44	45
	All Norite (Osann and Walker).	All Gabbro (Osann). .	All Basalt, including 161 Basalts, 17 Olivine Diabases, 11 Melaphyres, and 9 Dolerites (Osann).	Basalt, as named by Authors (including also Anamesite, Tachylite, etc.) (Osann).	Diabase (Osann).	Olivine Diabase (Osann).	Melaphyre (Osann).	Dolerite (Osann).
No. of Analyses.	7	41	198	161	20	17	11	9
SiO_2	50.16	48.24	49.06	48.78	50.12	50.10	50.60	49.50
TiO_2	1.64	.97	1.36	1.39	1.41	1.25	.68	1.42
Al_2O_3	18.51	17.88	15.70	15.85	15.68	14.43	17.40	14.37
Fe_2O_3	1.88	3.16	5.38	5.37	4.55	5.06	4.57	6.55
FeO	9.29	5.95	6.37	6.34	6.73	6.31	6.29	5.84
MnO	.14	.13	.31	.29	.23	.25	.46	.17
MgO	5.97	7.51	6.17	6.03	5.85	7.32	4.89	7.75
CaO	7.90	10.99	8.95	8.91	8.80	9.53	8.09	9.96
Na_2O	2.72	2.55	3.11	3.18	2.95	2.75	3.23	2.50
K_2O	.80	.89	1.52	1.63	1.38	.73	1.76	.84
H_2O	.76	1.45	1.62	1.76	1.93	2.00	1.83	.66
P_2O_5	.23	.28	.45	.47	.37	.27	.20	.44
Calculated as Water-free.								
SiO_2	50.54	48.95	49.87	49.65	51.11	51.12	51.54	49.83
TiO_2	1.65	.98	1.38	1.41	1.44	1.27	.69	1.43
Al_2O_3	18.65	18.15	15.96	16.13	15.99	14.73	17.73	14.47
Fe_2O_3	1.90	3.21	5.47	5.47	4.64	5.16	4.66	6.59
FeO	9.36	6.04	6.47	6.45	6.86	6.44	6.41	5.88
MnO	.14	.13	.32	.30	.23	.25	.47	.17
MgO	6.02	7.62	6.27	6.14	5.96	7.47	4.99	7.80
CaO	7.96	11.15	9.09	9.07	8.97	9.73	8.24	10.02
Na_2O	2.74	2.59	3.16	3.24	3.01	2.81	3.29	2.52
K_2O	.81	.90	1.55	1.66	1.41	.74	1.78	.85
P_2O_5	.23	.28	.46	.48	.38	.28	.20	.44
Each sum = 100.00.								

GROUP VII.

	Plutonics.				
	46	47	48	49	50
	Gabbro, excluding Olivine Gabbro (Osann).	Olivine Gabbro (Osann).	Norite, excluding Olivine Norite (Osann and Walker).	Olivine Norite (Osann).	Anorthosite (Osann and Washington).
No. of Analyses.	24	17	5	2	12
SiO_2	49.50	46.49	50.08	50.38	50.40
TiO_2	.84	1.17	1.44	2.04	.15
Al_2O_3	18.00	17.73	18.62	18.27	28.30
Fe_2O_3	2.80	3.66	2.35	.73	1.06
FeO	5.80	6.17	8.87	10.35	1.12
MnO	.12	.17	.11	.20	.05
MgO	6.62	8.86	6.22	5.32	1.25
CaO	10.64	11.48	7.89	7.91	12.46
Na_2O	2.82	2.16	2.53	3.18	3.67
K_2O	.98	.78	.71	1.02	.74
H_2O	1.60	1.04	1.01	.26	.75
P_2O_5	.28	.29	.17	.34	.05
Calculated as Water-free.					
SiO_2	50.31	46.97	50.60	50.51	50.78
TiO_2	.85	1.18	1.45	2.05	.15
Al_2O_3	18.30	17.92	18.81	18.32	28.51
Fe_2O_3	2.85	3.70	2.37	.73	1.07
FeO	5.89	6.24	8.96	10.38	1.13
MnO	.12	.17	.11	.20	.05
MgO	6.73	8.96	6.28	5.33	1.26
CaO	10.81	11.60	7.97	7.93	12.55
Na_2O	2.86	2.18	2.56	3.19	3.70
K_2O	1.00	.79	.72	1.02	.75
P_2O_5	.28	.29	.17	.34	.05
Each sum = 100.00.					

GROUP VIII.

	PLUTONICS.							EFFUSIVE.
	51	52	53	54	55	56	57	58
	Lhersolite (Osann).	Websterite (Osann).	Wehrlite (Osann).	Harsburgite, including Saxonite (Osann and Washington).	Dunite (Washington).	Pyroxenite (Osann).	All Peridotite (Osann).	Picrite (Osann).
No of Analyses.	4	4	3	4	3	4	49	3
SiO_2	42.09	53.65	48.13	43.85	40.06	49.82	44.39	43.24
TiO_2	.12	.14	.87	....	....	1.46	.88	....
Al_2O_3	4.83	1.66	6.50	5.00	.57	5.12	5.14	15.19
Fe_2O_3	4.98	1.90	2.01	2.54	2.29	1.83	3.88	8.62
FeO	4.58	5.35	11.73	6.30	7.32	7.44	6.70	7.89
MnO	.06	.17	.08	.12	.24	.09	.19	....
MgO	31.80	22.57	21.01	36.96	46.62	19.55	29.17	8.56
CaO	6.37	13.37	6.17	2.70	.35	13.00	6.31	13.78
Na_2O	1.02	.20	1.15	....	.01	.37	.64	.54
K_2O	.29	.07	.58	....	....	.21	.76	.48
H_2O	3.85	.85	1.62	2.53 [1]	2.53	1.06	1.80	1.21
P_2O_5	.01	.07	.15	....	.01	.05	.14	.49
Calculated as Water-free.								
SiO_2	43.78	54.11	48.93	44.99	41.10	50.36	45.20	43.77
TiO_2	.12	.14	.88	....	....	1.48	.90	....
Al_2O_3	5.02	1.67	6.61	5.13	.58	5.17	5.25	15.37
Fe_2O_3	5.18	1.92	2.04	2.61	2.35	1.85	3.95	8.72
FeO	4.77	5.40	11.92	6.46	7.51	7.52	6.82	7.99
MnO	.06	.17	.08	.12	.25	.09	.19	....
MgO	33.08	22.76	21.36	37.92	47.83	19.76	29.70	8.66
CaO	6.62	13.49	6.27	2.77	.36	13.14	6.43	13.95
Na_2O	1.06	.20	1.17	....	.01	.37	.65	.55
K_2O	.30	.07	.59	....	....	.21	.77	.49
P_2O_5	.01	.07	.15	....	.01	.05	.14	.50
Each sum = 100.00.								

[1] Loss on ignition.

GROUP IX.

	PLUTONIC.	EFFUSIVES.		
	59	60	61	62
	Essexite (Osann and Rosenbusch).	Trachydolerite (Rosenbusch).	Limburgite (Zirkel).	Augitite (Osann, Washington, and Rosenbusch).
No. of Analyses.	11	4	7	6
SiO_2	48.40	54.81	41.69	42.25
TiO_2	1.71	.42	.67	2.52
Al_2O_3	16.67	20.01	14.80	16.26
Fe_2O_3	5.31	3.98	15.04	8.43
FeO	6.03	1.93		5.46
MnO	.15	....	....	....
MgO	4.48	2.32	8.64	5.49
CaO	9.05	5.60	11.98	9.75
Na_2O	4.45	5.86	3.52	4.45
K_2O	2.13	3.13	1.17	1.92
H_2O	.95	1.46	2.36	2.43
P_2O_5	.67	.48	.13	1.04
Calculated as Water-free.				
SiO_2	48.86	55.62	42.69	43.30
TiO_2	1.73	.43	.68	2.58
Al_2O_3	16.83	20.31	15.18	16.67
Fe_2O_3	5.36	4.04	15.43	8.64
FeO	6.09	1.96		5.59
MnO	.15	....	....	....
MgO	4.52	2.35	8.85	5.63
CaO	9.14	5.68	12.27	9.99
Na_2O	4.49	5.94	3.58	4.56
K_2O	2.15	3.18	1.19	1.97
P_2O_5	.68	.49	.13	1.07
Each sum = 100.00.				

GROUP X.

	Plutonics.		Effusives.					
	63	64	65	66	67	68	69	70
	Theralite (Osann).	Shonkinite (Pirsson).	All Tephrite.	All Basanite.	Nephelite Tephrite (Osann).	Leucite Tephrite (Osann and Washington).	Nephelite Basanite (Osann).	Leucite Basanite (Osann and Washington).
No. of Analyses.	6	6	24	20	4	20	16	4
SiO_2	45.61	48.66	49.14	44.41	46.91	49.90	44.20	45.34
TiO_2	1.96	.97	1.00	1.56	1.81	.16	1.64	1.30
Al_2O_3	14.35	12.36	16.57	15.81	15.25	16.94	15.64	16.59
Fe_2O_3	6.17	3.08	3.65	4.66	7.70	3.02	4.35	5.83
FeO	4.03	5.86	6.68	5.85	4.06	7.15	6.14	4.76
MnO	.19	.13	.30	.14	1.43	.23	.19	.01
MgO	6.05	8.09	3.98	8.20	2.95	4.22	8.89	5.43
CaO	9.49	10.46[1]	9.88	10.12	9.36	10.04	9.74	11.64
Na_2O	5.12	2.71	2.57	3.81	4.25	2.24	4.03	2.93
K_2O	3.69	5.15	3.39	2.37	2.63	3.57	1.83	4.55
H_2O	2.60	1.46	2.00	2.42	2.51	1.74	2.67	1.12
P_2O_5	.74	1.07	.84	.65	1.14	.79	.68	.50
Calculated as Water-free.								
SiO_2	46.83	49.38	50.15	45.51	48.12	50.79	45.41	45.86
TiO_2	1.98	.98	1.02	1.60	1.86	.16	1.68	1.31
Al_2O_3	14.73	12.55	16.90	16.20	15.65	17.24	16.07	16.78
Fe_2O_3	6.34	3.12	3.72	4.78	7.89	3.07	4.47	5.90
FeO	4.14	5.95	6.82	5.99	4.16	7.28	6.31	4.81
MnO	.19	.13	.31	.14	1.47	.23	.20	.01
MgO	6.22	8.21	4.06	8.41	3.02	4.30	9.13	5.49
CaO	9.75	10.62[2]	10.08	10.37	9.60	10.22	10.01	11.77
Na_2O	5.27	2.75	2.62	3.90	4.36	2.28	4.14	2.96
K_2O	3.79	5.23	3.46	2.43	2.70	3.63	1.88	4.60
P_2O_5	.76	1.08	.86	.67	1.17	.80	.70	.51
Each sum = 100.00.								

[1] Includes .40% BaO and .09% SrO.

[2] Includes .41% BaO and .09% SrO.

GROUP XI.

	PLUTONICS.		EFFUSIVES.		PLUTONIC.	EFFUSIVES.	
	71	72	73	74	75	76	77
	Fergusite (Pirsson).	Missourite (Pirsson and Daly).	Leucite Basalt (Osann and Rosenbusch).	Leucitite (Osann and Rosenbusch).	Ijolite (Osann).	Nephelinite (Rosenbusch).	Nephelite Basalt (Osann).
No. of Analyses.	1	2	7	7	5	9	26
SiO_2	51.70	44.27	46.47	47.72	43.51	41.17	39.87
TiO_2	.23	1.37	1.33	.52	1.07	1.35	1.50
Al_2O_3	14.50	10.73	15.97	18.19	19.54	16.83	13.58
Fe_2O_3	5.07	3.63	5.97	4.74	3.77	7.61	6.71
FeO	3.58	5.87	4.27	3.90	3.88	6.64	6.43
MnO	.01	.06	.01	.06	.16	.16	.21
MgO	4.55	13.05	5.87	3.45	2.94	3.72	10.46
CaO	7.40 [1]	11.46 [2]	10.54	7.27	9.89	10.12	12.36
Na_2O	2.93	1.07	1.69	4.51	10.58	6.45	3.85
K_2O	7.60	4.43	4.83	7.66	2.26	2.49	1.87
H_2O	2.25	3.23	2.32	1.51	.86	2.42	2.22 [3]
P_2O_5	.18	.83	.73	.47	1.54	1.04	94.
Calculated as Water-free.							
SiO_2	52.89	45.75	47.58	48.45	43.89	42.19	40.77
TiO_2	.24	1.41	1.36	.53	1.08	1.38	1.53
Al_2O_3	14.83	11.09	16.35	18.47	19.71	17.25	13.88
Fe_2O_3	5.18	3.75	6.11	4.81	3.80	7.79	6.86
FeO	3.66	6.07	4.37	3.96	3.91	6.81	6.57
MnO	.01	.06	.01	.06	.16	.17	.21
MgO	4.65	13.49	6.01	3.50	2.97	3.81	10.73
CaO	7.57 [4]	11.85 [5]	10.79	7.38	9.98	10.37	12.65
Na_2O	3.00	1.10	1.73	4.58	10.67	6.61	3.94
K_2O	7.79	4.57	4.94	7.78	2.28	2.55	1.90
P_2O_5	.18	.86	.75	.48	1.55	1.07	.96
Each sum = 100.00.							

[1] Includes .30% BaO and .07% SrO.
[2] Includes .48% BaO and .18% SrO.
[3] Includes .29% CO_2.
[4] Includes .31 % BaO and .07 % SrO.
[5] Includes .50% BaO and .19% SrO.

GROUP XII.

	Plutonics.		
	78	79	80
	Alaskite (Osann).	Diorite of Electric Peak (Rosenbusch).	Malignite (Osann and Daly).
No. of Analyses.	3	10	4
SiO_2	76.47	62.21	50.34
TiO_2	.07	.60	.34
Al_2O_3	13.03	16.45	14.75
Fe_2O_3	1.04	2.53	4.18
FeO		2.89	2.75
MnO	.01	.02	.11
MgO	.06	3.32	4.23
CaO	.45	4.96	10.43
Na_2O	3.53	3.88 [1]	5.27
K_2O	4.81	2.21	5.21
H_2O	.52	.80 [2]	1.20
P_2O_5	.01	.13	1.19
Calculated as Water-free.			
SiO_2	76.87	62.71	50.95
TiO_2	.07	.60	.35
Al_2O_3	13.10	16.58	14.93
Fe_2O_3	1.05	2.55	4.23
FeO		2.92	2.78
MnO	.01	.02	.11
MgO	.06	3.35	4.28
CaO	.45	5.00	10.56
Na_2O	3.55	3.91 [1]	5.33
K_2O	4.83	2.23	5.27
P_2O_5	.01	.13	1.21
Each sum = 100.00.			

[1] Includes .07% Li_2O.

[2] Includes .05% Cl and .05% SO_3.

GROUP XIII.

	Effusives.						
	81	82	83	84	85	86	87
	Rhyolite of Yellowstone Park (Iddings).	Basalt of Hawaii (Osann).	Banakite (Osann).	Shoshonite (Osann).	Absarokite (Osann).	Leucite Absarokite (Osann).	Melilite Basalt (Osann).
No. of Analyses.	10	11	4	8	5	2	6
SiO_2	74.04	48.36	52.04	53.56	50.11	47.45	36.19
TiO_2	.18	.66	.76	.82	.96	.81	7.11
Al_2O_3	13.19	15.40	17.65	17.88	13.04	11.43	10.52
Fe_2O_3	1.35	6.48	4.66	4.51	4.58	3.22	8.48 [1]
FeO	1.01	10.07	2.75	3.05	3.94	5.78	5.97
MnO	.04	.80	.13	.07	.11	.12	....
MgO	.32	4.19	3.33	3.62	9.27	14.60	14.59
CaO	1.19	8.69	5.11	6.45	7.63	8.18	9.88
Na_2O	3.88	3.34	4.10	3.41	1.94	2.32	3.28
K_2O	3.75	1.30	5.03	3.76	4.15	2.99	2.03
H_2O	1.02 [2]	.43	3.74	2.32	3.58	2.50	1.94 [3]
P_2O_5	.03	.28	.70	.55	.69	.60	.01
Calculated as Water-free.							
SiO_2	74.80	48.57	54.06	54.84	51.97	48.67	36.90
TiO_2	.18	.66	.79	.84	1.00	.83	7.25
Al_2O_3	13.33	15.47	18.34	18.31	13.52	11.73	10.73
Fe_2O_3	1.37	6.51	4.84	4.62	4.74	3.30	8.65 [4]
FeO	1.02	10.11	2.85	3.12	4.08	5.93	6.09
MnO	.04	.80	.14	.07	.12	.12	....
MgO	.32	4.21	3.46	3.70	9.62	14.97	14.88
CaO	1.20	8.73	5.31	6.60	7.91	8.39	10.08
Na_2O	3.92	3.35	4.26	3.49	2.01	2.38	3.34
K_2O	3.79	1.31	5.22	3.85	4.31	3.06	2.07
P_2O_5	.03	.28	.73	.56	.72	.62	.01
Each sum = 100.00							

[1] Includes 2.85 % Cr_2O_3.

[2] Includes .02 % Li_2O and .23 % SO_3.

[3] Loss on ignition.

[4] Includes 2.47 % Cr_2O_3.

GROUP XIV.

Dike-rocks.					
	88	89	90	91	92
	Granite-aplite (Osann and Washington).	Bostonite (Rosenbusch and Washington).	Grorudite (Osann and Washington).	Sölvsbergite (Osann and Washington).	Tinguaite (Osann and Washington).
No. of Analyses.	15	5	5	8	15
SiO_2	75.00	61.32	70.91	62.16	55.02
TiO_2	.30	.89	.48	.31	.36
Al_2O_3	13.14	18.43	11.50	17.58	20.42
Fe_2O_3	.58	3.84	4.58	3.05	3.06
FeO	.40	1.60	1.88	1.80	1.82
MnO	.07	.01	.39	.18	.22
MgO	.30	.46	.11	.48	.59
CaO	1.13	1.45	.39	1.11	1.67
Na_2O	3.54	5.75	5.43	7.30	8.63
K_2O	4.80	4.94	4.08	4.95	5.38
H_2O	.71	1.31	.25	1.04	2.77
P_2O_5	.03	....	....	.04	.06
Calculated as Water-free.					
SiO_2	75.54	62.14	71.09	62.82	56.59
TiO_2	.30	.90	.48	.31	.37
Al_2O_3	13.23	18.67	11.53	17.77	21.00
Fe_2O_3	.58	3.89	4.59	3.08	3.15
FeO	.40	1.62	1.89	1.82	1.87
MnO	.07	.01	.39	.18	.23
MgO	.30	.47	.11	.49	.61
CaO	1.14	1.47	.39	1.12	1.72
Na_2O	3.57	5.82	5.44	7.37	8.87
K_2O	4.84	5.01	4.09	5.00	5.53
P_2O_5	.03	....	....	.04	.06
Each sum = 100.00.					

GROUP XV.

	Dike-rocks.					
	93	94	95	96	97	98
	Minette (Osann and Clarke).	Kersantite (Osann and Rosenbusch).	Vogesite (Osann).	Camptonite (Osann).	Monchiquite (Osann).	Alnöite (Osann and Washington).
No. of Analyses.	10	20	4	15	16	6
SiO_2	49.45	50.79	52.62	40.70	45.17	32.31
TiO_2	1.23	1.02	.54	3.86	1.90	1.41
Al_2O_3	14.41	15.26	14.86	16.02	14.78	9.50
Fe_2O_3	3.39	3.29	3.60	5.43	5.10	5.42
FeO	5.01	5.54	4.18	7.84	5.05	6.34
MnO	.13	.07	.84	.16	.35	.01
MgO	8.26	6.33	8.55	5.43	6.26	17.43
CaO	6.73	5.73	5.86	9.36	11.06	13.58
Na_2O	2.54	3.12	3.21	3.23	3.69	1.42
K_2O	4.69	2.79	2.83	1.76	2.73	2.70
H_2O	3.04[1]	5.71[2]	2.70	5.59[3]	3.40	7.50[4]
P_2O_5	1.12	.35	.21	.62	.51	2.38
	Calculated as Water-free.					
SiO_2	50.99	53.87	54.08	43.10	46.76	34.93
TiO_2	1.27	1.08	.56	4.09	1.96	1.52
Al_2O_3	14.86	16.18	15.28	16.97	15.30	10.27
Fe_2O_3	3.50	3.48	3.70	5.76	5.28	5.86
FeO	5.17	5.88	4.29	8.30	5.23	6.85
MnO	.13	.07	.86	.16	.36	.01
MgO	8.53	6.71	8.79	5.76	6.48	18.84
CaO	6.95	6.09	6.02	9.92	11.45	14.68
Na_2O	2.62	3.31	3.30	3.42	3.82	1.53
K_2O	4.84	2.96	2.90	1.86	2.83	2.92
P_2O_5	1.14	.37	.22	.66	.53	2.59
	Each sum = 100.00.					

[1] Includes .61% CO_2.

[2] Includes 2.61% CO_2.

[3] Includes 2.97% CO_2.

[4] Includes 4.35% CO_2.

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AVERAGE SPECIFIC GRAVITIES OF CERTAIN TYPES.

The average specific gravities of holocrystalline types have been calculated, with result shown in the following accessory table. Most of the determinations were taken from Osann's book.

	Number of Specimens averaged.	Average Specific Gravity.
Granite	58	2.660
Granodiorite	5	2.740
Syenite	11	2.773
Monzonite	2	2.805
Nephelite syenite	13	2.600
Diorite	17	2.861
Gabbro	19	2.933
Olivine gabbro	4	2.948
Anorthosite	6	2.715
Peridotite	21	3.176
Essexite	2	2.862
Theralite	3	2.917
Malignite	4	2.884

SOME APPLICATIONS.

The uses to which the averages may be put are diverse and, in certain instances, direct and important. A brief note in this place will indicate something of the range of the considerations affected.

1. The writer has found from personal experience that the averages have been of decided benefit in showing the chemical individuality and true nature of the igneous-rock types as actually mapped. To student and investigator alike such averages are, for many purposes, more valuable than single analyses. They help to show that eruptive rocks

do not form an infinite series, but that the varieties cluster about "center-points." Osann's great compilation proves that Rosenbusch's classification is an objective and "natural" one to a highly useful degree.

2. The obvious error involved in computing "the average composition of the primitive crust of the earth," or "the average igneous rock," or "the mean composition of the accessible parts of the earth's crust," by averaging a large number of analyses compiled at random, has not deterred a goodly number of authors from using such results as those deduced by Clarke, Washington, and Harker. These averages are bound to breed further errors when used as a basis for quantitative studies in geology or oceanography. The discovery of "the average igneous rock" is of the highest importance for many problems such as the chemical denudation of the lands and the chemical evolution of the ocean. The mean composition of the accessible crystalline rocks of the globe must ultimately be obtained by taking account of the relative volumes of the different rock-types. In computing the mean the average analyses for the principal individual species must be employed. Since the only approach to success is through the quantitative study of geological maps and memoirs, it is clear that for many years to come the averages for the types recognized in Rosenbusch's system are to be basal to the calculation.

A glance at Table II. shows, however, that this new world-average will differ little from the earlier world-averages with respect to one oxide, namely, soda. For each of the areally and volumetrically important rock-types the average soda never departs far from a mean of about three and one half per cent. The soda in the averages of Clarke, Washington, and Harker (calculated as water-free) is, respectively, 3.63 per cent, 3.34 per cent, and 3.90 per cent.[1] The agreement is fortunate, since, for example, the quantitative problem relative to the sodium in the ocean can be pursued without waiting for the close determination of "the average igneous rock." Incidentally, it may be remarked that the estimates of Joly[2] and Sollas[3] regarding the age of the ocean, as determined by the sodium content, need revision, since neither author has allowed for the great variations in the area of the lands during geological time.

3. The recurrence of the main types of igneous rock in every continent shows that general processes of differentiation have been at work

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[1] F. W. Clarke, Bull. 228, U. S. Geol. Survey, 1904, p. 16.

[2] J. Joly, Sci. Trans. Roy. Dublin Society, **7**, 23 (1899).

[3] W. J. Sollas, Quart. Jour. Geol. Soc., Presidential Address, **65**, p. lxxix (1909).

from the earliest recorded time. There is no reason to doubt that the diorite or the nephelite syenite of the pre-Cambrian periods have generally owed their origin to the same physico-chemical reactions as those responsible for the Mesozoic or Tertiary diorite or nephelite syenite. If this be true, the world-averages for the different principal types should be so many tests of theoretical conclusions as to the causes of the differentiation of those types. The question as to the derivation of augite andesite from basalt through fractional crystallization has been thus tested, with, so far as this test goes, an affirmative answer.[4]

Sometimes the averages themselves suggest lines of thought. For example, the average granite analysis (calculated water-free; 236 analyses) is close to the average of four analyses of the glassy base of augite andesite (calculated as water-free). The comparison may be made from the following table:

	Granite of all Periods.	Ground-mass (base) of Augite andesite.
No. of Analyses	**236**	**4**
	per cent.	per cent.
SiO_2	70.47	69.31
TiO_2	.39	....
Al_2O_3	14.90	17.11
Fe_2O_3	1.63	2.15
FeO	1.68	.60
MnO	.13	....
MgO	.98	.70
CaO (BaO and SrO)	2.17	2.63
Na_2O	3.31	3.20
K_2O	4.10	4.30
P_2O_5	.24	....
	100.00	100.00

The exact meaning of the correspondence between the two averages may not be discussed here; but it does suggest an explanation of the common association of granites (and liparites) with andesites (and diorites) in nature. The question is open as to whether the primitive granite-liparite magma was not a polar differentiate of an andesitic magma, preferably by a settling-out of the phenocrystic constituents (in solid or liquid phases)from the andesitic magma.

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[4] Journal of Geology, 16, 401 (1908).

Other related questions are raised by the comparison of the mean of average granite and average basalt with average diorite (including quartz diorite).

	1. Average Granite.	2. Average Basalt.	3. Mean of 1 and 2.	4. Average Diorite.
No. of Analyses	236	161	—	89
	per cent.	per cent.	per cent.	per cent.
SiO_2	70.47	49.65	60.06	59.19
TiO_2	.39	1.41	.90	.81
Al_2O_3	14.90	16.13	15.52	16.51
Fe_2O_3	1.63	5.47	3.55	3.02
FeO	1.68	6.45	4.06	4.17
MnO	.13	.30	.21	.13
MgO	.98	6.14	3.56	3.93
CaO	2.17[1]	9.07	5.62	6.47
Na_2O	3.31	3.24	3.28	3.39
K_2O	4.10	1.66	2.88	2.12
P_2O_5	.24	.48	.36	.26
	100.00	100.00	100.00	100.00

[1] Includes .06% BaO and .02% SrO.

Is basalt the basic pole, granite the acid pole, of a primitive differentiation of diorite magma? Is diorite the product of mixture of primitive, granitic crust and primary basalt still molten beneath? Though the averages give no answer, they tend to keep these fundamental queries before the eye of the petrologist.

4. The averages have been arranged so as generally to place

together those of plutonics and the corresponding effusive rocks. The comparisons show the truth of Rosenbusch's statement that the effusives are, on the whole, somewhat higher in silica and alkalies and lower in iron oxides, lime, magnesia, etc., than the respective plutonics.

The importance of this rule is at least two-fold. It proves the value of Rosenbusch's primary division into the deep-seated types and the surface lavas. It shows therewith one of the reasons why the Norm[5] Classification of igneous rocks is largely a failure so far as either the field-geologist or the student of petrogeny is concerned.

Secondly, the rule suggests clearly that at volcanic vents there is a general cause for the removal of iron, magnesium, and calcium oxides from the magmatic columns and that the cause is more effective in volcanic vents than in the average plutonic body. The cause is most probably to be found in the gravitative settlement of part of the ferromagnesian and other constituents of early crystallization. These constituents may settle out either as solid crystals or as liquid fractions immiscible near the consolidation point of the magma. Since, on the average, the column of fluid magma is taller in an active volcanic vent than in a plutonic mass, the overlying phase of the splitting magma should be, in general, slightly more acid and alkaline than the corresponding pole of differentiation in a deep-seated mass. In the nature of the case the more acid-alkaline pole is the one most liable to flow out at the surface. Though volcanic vents are much narrower than plutonic chambers and therefore subject to quicker chilling, with a resulting check to differentiation, this tendency is largely counterbalanced by the passage of very hot gases through vents. The mere agitation in the vents facilitates the separation. Whatever additional considerations are necessary to complete the comparison, it must here suffice to note that, as a rule, the laws of solution as applied to magmas seem to demand a differentiation with slow cooling, whereby a surface lava is less basic and ferromagnesian than the plutonic body feeding the vent of that lava. The corroboration of Rosenbusch's above-mentioned rule through the world-averages appears, therefore, to be of use in illustrating one of the world-wide influences controlling the origin of igneous rocks.

Some special conclusions regarding classification may be noted. From the averages it is evident that dacite is the effusive correspondent of granodiorite and not of quartz diorite. The contention of

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[5] Quantitative Classification of Igneous Rocks, by W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, Chicago and London, 1903.

American geologists that the vast development of granodiorite in the Cordilleras of North and South America should alone give the name a primary place in rock classification, is again justified. The many occurrences of dacite throughout the world represent just so many additional masses of cooled magma which were chemically identical with, or closely related to granodiorite. In volumetric importance, as in mineralogical and chemical individuality, the granodiorite type should rank as of the same order as granite itself.

Quartz porphyry, liparite, and rhyolite show that essential identity of composition which has long been apparent from more qualitative comparison.

5. There is little noteworthy chemical difference between the average pre-Cambrian granite and the average granite of later periods. How far the differences in alumina and potash (columns 1, 2, and 3) are due to the relative fewness of analyses of pre-Cambrian types cannot be stated. In spite of any such uncertainties the stability of the chemical type represented by granite throughout geological time is manifest. The explanation of the fact may well be found in Vogt's idea that granite is an "anchi-eutectic," a crystallized mother-liquor, a nearly extreme product of magmatic differentiation. It is possible that some of the older pre-Cambrian granite represents the differentiation of primeval magma. For many reasons it seems probable that most, if not all, post-Cambrian granites are differentiates from syntectic magma, chiefly composed of primary basaltic magma which has locally redissolved the ancient, acid shell overlying. In such case the splitting of the syntectic would ultimately give an acid differentiate similar to that formed in the primitive time. In general, differentiation in batholiths, when well advanced, restores the condition temporarily disturbed by magmatic assimilation. On this (confessedly hypothetical) view one may feel no surprise in noting a fairly steady composition in the granites from the average oldest type to the average youngest.

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STUDIES ON THE SO-CALLED PORPHYRITIC GNEISS OF NEW HAMPSHIRE.

CONTENTS.

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Introduction.—The following paper embodies the results of some weeks of field work on the New Hampshire terrane, heretofore considered by some writers to be a metamorphosed Archæan sediment, but suspected by others to be eruptive. The conclusions of the author corroborate this suspicion and he has attempted to express them here with the special point in mind. The author desires to express his best thanks to Professor J. E. Wolff, of Harvard University, for valued suggestions and very material aid during the progress of the work.

Historical summary of opinion on the "porphyritic gneiss."—From the conspicuous nature of its outcrops the "porphyritic gneiss" of New Hampshire early attracted the attention of geologists. In the first annual report of the Jackson survey, in 1841, Whitney and Williams, in describing its occurrence remark that "large bowlders of porphyritic granite are very numerous over the surface, from the west parish of Concord to the center of Warner, where we find the rock itself in place. It is a peculiar rock, having large crystals of feldspar uniformly distributed through its mass; they are often glassy, so as to furnish beautiful and striking specimens. This bed of granite extends across the state in a general northeast and southwest direction. It is from eight to ten miles in width, though often interrupted with veins of granite of various texture."[1] With the physical difficulties of a rugged, forest-clad country, it was not to be expected that accurate determinations of boundaries could be made by these geological pioneers. To this fact is due the confusion of the "porphyritic gneiss" and associated schists in the published Portsmouth-Claremont section of the Final Report.

In their section, "from Haverhill to the White Mountains," Whitney and Williams again refer to the formation thus: "From Meredith to Centre Harbor the rock in place is porphyritic granite, often traversed by beds and veins of fine grained, dark colored granite and trap. Some specimens of the porphyritic granite, in which the crystals of feldspar are flesh colored, are very beautiful. . . . . "From Centre Harbor to Plymouth the rock in place is porphyritic granite, traversed by occasional beds of mica slate."[2]

The first distinct mention of the "porphyritic gneiss" in the second (and last) survey of the state, that under the control of Professor C. H. Hitchcock, occurs in the second annual report, 1870. The preliminary map issued with that report roughly outlines the formation which he calls porphyritic granite. He describes it as "common granite full of large crystals of feldspar, generally from one-half of one to two inches long, which gives a checked appearance to the ledges. Some portions of it have evidently been injected, while the arrangement of the feldspathic crystals in parallel lines leads to the suspicion of stratification in other cases. When accurately mapped the area will resemble the trunk and branches of a decayed tree, the branches corresponding to the veins which have been injected from the original mass.[1]

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[1] Final Report on the Geol. of N. H., C. T. JACKSON, 1844, p. 51.

[2] Op. cit. pp. 73 and 137.

In the report for the next year, Professor Hitchcock adopted the view which was held throughout the later publications of the survey. On the map, of a scale of five miles to one inch, he differentiates the Lake Winnipiseogee and White Mountain areas, and gives a brief description of the rock, to which he affixes the name "porphyritic gneiss." He says: "This is an ordinary gneiss, carrying numerous crystals of orthoclase or potash-feldspar, from a quarter of one to two inches long. The longer axes may be parallel to the strike or arranged helter-skelter. It passes into granite with the same porphyritic peculiarity of structure. . . . . We suppose this to be the oldest formation among the mountains. Geologists speak of a rock of this character as common in the Laurentian in various parts of North America and Europe."[2]

At the twenty-first meeting of the American Association for the Advancement of Science, held in 1872, Professor Hitchcock expressly referred the "prophyritic gneiss" to the Laurentian[3] and noted the common parallel structure of the rock which he concluded to be the trace of an almost obliterated stratification.[4]

An indication of doubt as to an exact correlation appears in Professor Hitchcock's "Classification of the Rocks of New Hampshire," published in 1873.[5] He divides the various formations of the lower series into two groups—the Laurentian, which he qualifies by an interrogation point, and the Labradorian. The former included the "porphyritic gneiss," Bethlehem gneiss, White Mountain, or andalusite-gneiss, and the breccia of Franconia, in the order of decreasing age. The eight members of the Labradorian "constitute one horizontal series of formations, the lowest resting upon the upturned edges of all the parts of group I." The greater antiquity of the "porphyritic gneiss" than that of the other series "is inferred from the occurrence of several bands of andalusite and granitic gneisses upon both flanks." It is interesting to note that in discussion on this paper Dr. C. T. Jackson declared his belief that "the classification proposed was hypothetical to a great extent, and that sufficient reason for the adoption of the New York nomenclature was not shown."

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[1] Second Ann. Rep. upon the Geol. and Mineralogy of N. H., 1870, p. 33.

[2] Geology of New Hampshire, 1874, Vol. I, p. 33.

[3] Explanation of a New Geological Map of New Hampshire. Proc. A. A. A. S., 1872, p. 134.

[4] Recent Geological Discoveries among the White Mountains, N. H. Proc. A. A. A. S., 1872, p. 135. In this paper the author states his grounds for the correlation, viz., that of lithological similarity between the porphyritic gneiss and the Laurentian of Canada and Europe. At each of the next two meetings of the Association, he reaffirmed his position that there is nothing older in the state than the porphyritic gneiss which was held to be Archæan in age. See Geological History of Lake Winnipiseogee. Proc. A. A. A. S., 1873, B. p. 122, and the Physical History of New Hampshire, *ibid.*, 1874, B. p. 76.

[5] Proc. Bos. Soc. Nat. Hist., Vol. XV., p. 304.

The first volume of the Final Report of the Hitchcock Survey was issued in 1874. The "porphyritic gneiss" was there explained as the product of altered sediment, the primitive stratified rocks having been metamorphosed in Archæan, or, as then expressed, Eozoic time.[1] The second volume, published three years later, reiterated this opinion, making the terrane the representative of the "first territory in the state that was redeemed from the primeval ocean."[2]

"A porphyritic, or augen-gneiss, is eminently characteristic of the fundamental rocks in every part of the world, and hence ours may readily be called Laurentian."[3] A still closer correlation was suggested whereby the "porphyritic gneiss" of the White Mountain district, and inferentially that of the whole state, was put in the "upper division of the Laurentian system, as it is developed in Canada and New York."[4] In the general résumé of the stratigraphical relations, a thickness of five thousand feet was estimated for the formation. With it was included the "younger Bethlehem and Lake Winnipiseogee gneisses to form the whole Laurentian, aggregating 34,900 feet in thickness.[5]

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[1] Geol. of N. H., Vol. I., 1874, p. 512.

[2] Geol. of N. H., Vol. II, 1877, p. 519.

[3] *Ibid.*, p. 668.

[4] *Ibid.*, p. 252.

[5] *Ibid.*, p. 668.

From this brief review it is seen that the placing of the "porphyritic gneiss" so low in the geological scale was largely due to the prevalence of two pernicious doctrines then held in the study of crystalline schists. The application of the "lithological canon" was a constant feature in the efforts of the second survey to work out their difficult field. The coarse granitic gneisses, the augen-gneiss, and the andalusite-gneiss were each supposed to be represented in the typical Laurentian of the better known regions, thereby establishing synchrony. Again the distinct foliation in many parts of the "porphyritic gneiss" led to the other serious error of considering the rock as a metamorphosed sediment, which still preserved traces of its original planes of stratification.[1] This position being taken, it was but natural to look for structural relations with the surrounding formations, and at many contacts, the greater antiquity of the porphyritic rock would often appear evident. Needless to say, however, in the light of present knowledge, that all such reasoning is without foundation so far as it refers to large isolated areas of thoroughly crystalline schists. Thus the character of the terrane had to be determined by other methods. The latter were very sparingly used by the survey, and consequently its final conclusions assigned to the "porphyritic gneiss" the very important position of a foundation member in the entire geological series.

The interpretation of other terranes was, of course, greatly influenced by this fundamental idea. The survey fixed the geological position of the Bethlehem gneiss,[2] and of the Montalban group and the Lake Winnipiseogee gneiss [3] directly by reference to the "porphyritic gneiss," and the later succession was correspondingly affected. In fact, Professor T. Sterry Hunt's conception of and nomenclature of the Montalban group was founded on the conclusion that there is this demonstrable Laurentian in New Hampshire.[4]

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[1] Geol. of N. H., Vol. II, p. 99.

[2] 1871. See Geol. of N. H., Vol. I, p. 34; Vol. II, p. 452.

[3] *Ibid.*, Vol. II, pp. 564,662.

[4] Geol. Mag., 1887, p. 1499; Nature, Sept., 1888, p. 521.

We have already referred to some hints of an igneous, intrusive origin for the "porphyritic gneiss," that were given by the survey officers. Similar suggestions appear in many parts of the different reports.[1] The facts described in these passages were supposed to be explained on the metamorphic theory as being characteristic of only those parts of the ancient stratified rocks which had been altered to the extent of complete fusion.

In his address as vice president of section *E* of the American Association in 1883, Professor Hitchcock expressed some modification of his earlier opinions on the origin of the porphyritic gneiss. He said: "A careful study of the crystalline rocks of the Atlantic slope indicates the presence of scattered, ovoidal areas of Laurentian gneisses. Those best known have been described in the geology of New Hampshire. Instead of a few synclinal troughs filled to great depths with sediments, the oldest group is disposed in no less than twenty-two areas of small size, scattered like the islands in an archipelago.[2] There are no minerals in these Laurentian islands that do not occur in eruptive granite; and the schistose structure is often so faint that the field geologist need not be blamed if he acknowledges his inability to detect it. Likewise we discover the same fluidal inclusions and the vacuoles that pertain to granite."[3] Comparing these islands to volcanic oceanic islands of the present day, he suggests that the foliation of the porphyritic gneiss may be the result of the superposition in quaquaversal sheets of lava about each volcanic cone, aided by flows of mud and wear by water between igneous flows. In this way we might have a "concentric statiform arrangement in the whole mass." Subsequent metamorphism by heat and pressure would lead to the development of new minerals in foliated beds.

The next important notice of this formation appears in Whitney and Wadsworth's "Azoic system."[4] They instituted a close

[1] See Geol. of N. H., I, pp. 27, 33; II, pp. 102, 472, 520.

[2] Proc. A. A. A. S, 1883, E., p. 186.

[3] Op. cit., p. 187.

[4] Bull Mus. Comp. Zoöl., Harvard College, Vol. VII, 1884, p. 383 ff.

criticism of the general methods of the New Hampshire survey, and looked with especial disfavor upon the liberal use of the "lithological canon," as accepted by the members of that survey. A convenient résumé of the various classifications proposed for New Hampshire rocks is given in tabular form at page 396 of the memoir. The possibility of an eruptive origin for the "porphyritic gneiss" was remarked by the authors.

In 1884 Professor Hitchcock stated that "all thoroughly crystalline series of the Atlantic region are of Eozoic age."[1] Two years later he edited the "Geological Map of the United States," in which the "porphyritic gneiss" is colored as Laurentian.[2] A somewhat full account of his opinions on the formation was given in a paper on the "Significance of Oval Granitoid Areas in the Lower Laurentian,"[3] from which it is evident that in 1890 Professor Hitchcock held practically the same views on the present subject as those which he published in 1883.

While the present paper was in process of preparation the last word on the formation was given by Professor Hitchcock in this JOURNAL. After tracing in a general way the history of geological surveying in New Hampshire, he makes the following significant statement of a changed point of view: "The question now arises, how can our early classification [of the rock series] be improved? It is eighteen years since the New Hampshire report was published, and there are many new workers in the field, all placing great reliance upon petrographical principles, such as were inaugurated in Dr. Hawes' report. Some are advocates of extreme metamorphism, and hence the conclusions are not harmonious. It seems to us that our early views may be modified by the following principles: (1) The mineral characters of crystalline rocks are not a sure guide to geological age. (2) Protogenes, diabases, and diorites, more or less interstratified with hydro-micas, are of true igneous origin. (3) The

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[1] Trans. Am. Inst. Min. Eng. XII, 1884, p. 68. Cf. a paper in Proc. A. A. A. S. of the same year (p. 396) where he again holds the porphyritic gneiss to be Laurentian.

[2] Trans. Am. Inst. Min. Eng., Vol. XV, 1886, p. 465.

[3] Bull. Geol. Soc. Am., I, 1890, p. 557.

Archæan gneisses and protogenes may also be of igneous origin, and their apparent stratification has no connection with sedimentary or chemical deposition, etc. . . . . Applying such principles to the classification of the rocks of northern New England, we may improve on the report in several particulars. (1) Archæan rocks are not eliminated from our list. They exist as oval areas, such as have been indicated in the Stamford gneiss, and south of Mount Killington, Vt., in the Hinsdale, Mass., area, the Hoosac Mountain, and elsewhere. I recognize the porphyritic gneiss in the Stamford rock, and in the Hoosac tunnel as Archæan. (2) Our hesitancy about the place of the Bethlehem gneiss is met by recent observations. They are batholites, containing inclusions of the adjacent mica-schists. It does not follow that all these protogene areas are of the same character; each one must be studied by itself."[1]

However satisfactory such conclusions may be in their application to most of the formations in the state, a clear statement of the true relations of the porphyritic gneiss has not yet been made. The author's recognition of the correct methods which must be used in interpreting crystalline schists has as yet not been supplemented very largely by their positive exercise in the field, and the implication in the foregoing extract that the Archæan appears in the state in "oval areas," either igneous or non-igneous, is still without demonstration.

We shall hereafter adhere to the name porphyritic granite, for the rock under discussion instead of porphyritic gneiss which has been so far used. As will appear later, the former name, while not embodying all the generalized features of the rock, is preferable to the official one of the second geological survey.

Geographical distribution.—The porphyritic granite, as shown on the survey maps, occupies four large areas with several smaller ones. Of these the largest one extends from Mount Monadnock, N. 5° E. to the northern flank of Cardigan Mountain, a distance of sixty miles; while it varies from three to twelve miles in width. Since this occurrence covers more than four times as many square miles as any other, it may well be called the "Main area." Associated with it in Sullivan, Merrimack, and Hillsboro counties, are some half dozen much smaller outcrops of the same rock which are surrounded by schists, and are thus outliers from the larger mass. Twelve miles west by south of Mount Monadnock, a second important mass of regular elliptical or oval-shape cuts cross the Ashuelot division of the Boston and Maine railroad. The longer axis runs north and south, and is about ten miles long, while the shorter, transverse to the former, is six miles long. From the village of Ashuelot, situated on porphyritic granite, we shall derive a distinctive name, and call this the "Ashuelot area." The survey has mapped a large "White Mountain area," which is distributed in irregular elongated form at the north of the Main area from Mount Stinson to Mount Lafayette. Some twenty miles long, it also varies considerably in width, being only a mile wide near the Profile House, but broadening out to six miles at the Kinsman Notch. From there a long tongue of the rock runs southerly down the valley of the Pemigewasset River. The strike of this area is like that of the Main area, a few degrees east of north. Following the common axis of both areas northward from the Profile House, a small but important "Littleton area" of some eight or ten square miles in extent, appears near the town of Littleton. The fourth widespread occurrence of the porphyritic granite is found in another irregular mass thirty miles long, and from one to eight broad, running parallel to the Main area from Laconia to Waterville. This may be referred to as the "Winnipiseogee area," from its proximity to the beautiful lake of that name.

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[1] The Geology of New Hampshire. JOUR. GEOL., Chicago, Vol. IV, 1896, p. 57.

The very local outcroppings of this rock in other parts of the state are in point of size insignificant, but they are of value in helping to determine the relations of the whole formation. Notable among these are the small patch on the top of Mount Prospect west of Squam Lake and the long dikelike mass north of New Boston in Hillsboro county. The grounds for coloring in the mass of porphyritic granite at the southeast base of Mount

Monadnock did not appear to be corroborated by the present writer in a somewhat careful study of that region. The mantle of glacial drift is there very heavy, but the few outcrops which were discovered seemed to prove the bedrock to be of the same nature as the schists round about. Again, a visit to Mount Osceola showed that the area of porphyritic granite plotted on the survey map as occurring on its southern side is really occupied by the same coarse-grained hornblende-granite which occurs in the bed of Mad River, the "Conway Granite" of the survey.

So great being the extent of the formation, it was impossible in the time at the disposal of the writer to make a close examination of all parts of the porphyritic granite. Accordingly, most of the observations in the following pages refer to three areas, the study of which promised to be most fruitful in the problem before us. Those selected were the Winnipiseogee area, the Ashuelot area, and the contact of the Main area from the town of Jaffrey to Henniker on the Peterboro and Hillsboro branch of the Boston and Maine Railroad. We shall consider these areas separately, treating of the geological results obtained in each along with certain other facts whose arrangement would be difficult by any other method of discussion.

Brief description of the porphyritic granite.—General macroscopical descriptions of the granite are given in several parts of the "Geology of New Hampshire." The rock is remarkably simple in its phasal differentiation; so far as a considerable collection shows, there are only two important variations in it throughout its whole extent. It may be either a porphyritic granitite or a porphyritic granite proper, and either of them may have the foliated structure. They pass into each other by insensible gradation in all the areas and it seems to be impossible to map them separately. With the exception of this and a few other variable features noticed in the sequel, the porphyritic granite is essentially uniform; it is thus possible to dismiss its characterization in a comparatively summary manner. In a future paper, the author hopes to give an account of certain petrographical features whose description here is not rendered either advisable or necessary for our present purpose.

The name "porphyritic granite" for this rock is regarded as the best available one both on the ground of inherent meaning and of precedent. The composition and order of crystallization make it a true granite rather than a gneiss although the pseudo-schistose structure is so generally present. For very similar rocks, the names "granite-porphyry," "gneissic granite," etc.,

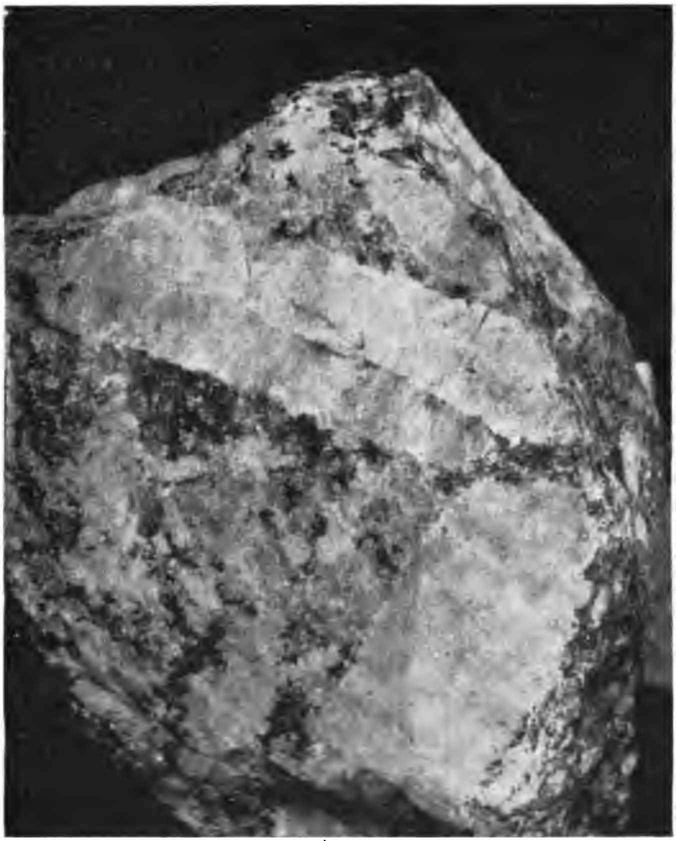

FIG. 1.— Photograph of a specimen of the porphyritic granite — obtained near New Hampton Centre — illustrating general habit of granitic phase, twinned phenocrysts, etc.— about natural size.

have been employed. It seems best to use the original name at first used by each of the New Hampshire surveys and in this we follow the nomenclature of Lehmann, Sederholm, Gümbel and others who have dealt with very similar rocks.

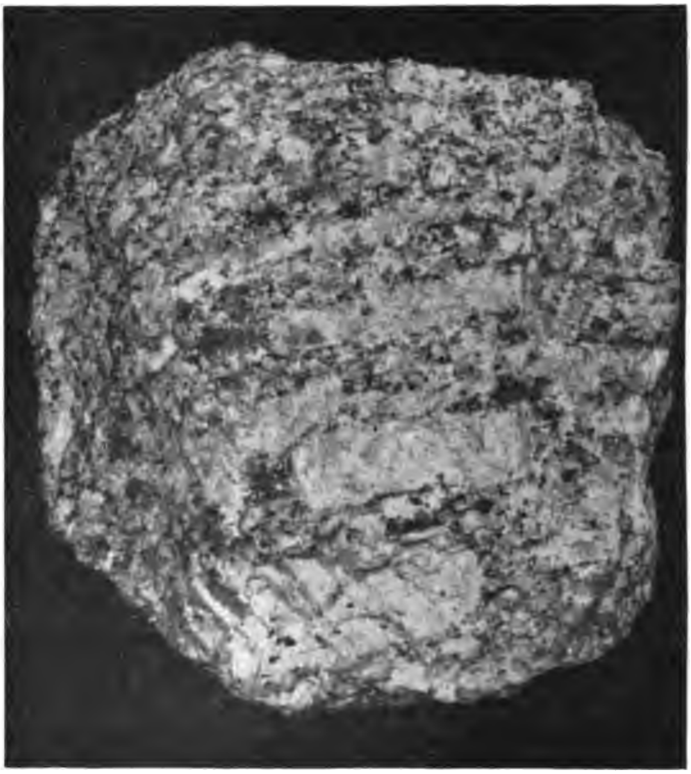

FIG. 2.— Photograph of a specimen of the porphyritic granite, showing a foliated phase near Hancock Station. The lowest phenocryst displays two prismatic partings besides the normal cleavages, parallel to *P* and *M*. The base is nearly in the plane of the paper. About one-half natural size.

The granite is always striking and handsome in appearance The groundmass is a coarse-grained, light to dark gray, granular aggregate of quartz and feldspar interspersed with flecks, blotches and lines of greenish muscovite and brilliant brown biotite.

Within are embedded the lustrous phenocrysts which generally, though not always, lie in the foliation plane when the rock has the plane-parallel structure.

The phenocrysts are glassy to opaque white and seem to be in every case either orthoclase or microcline, which may be intergrown with another (triclinic) feldspar in the usual microperthitic fashion. The largest ones are as much as twelve centimeters long. The usual habit is that of simple Carlsbad twins. They present straight edges to the surrounding matrix, giving the planes (001) (010) (110) and (101). This idiomorphic appearance is often lost in the slide through the great amount of resorption and marginal corrosion. Occasionally small shreds of biotite, a minute individual of apatite, or a few grains of quartz may appear in the core of the feldspar, but as a rule it is notably free from primary inclusions. The results of decomposition are normal. The changing to a reddish hue is common in some weathered phases.

The matrix of the rock is simply a typical coarse granitite on the one hand or a granite proper (in the classification of Rosenbusch) on the other, in either case with or without the foliated structure. The feldspars have the same general characters as those of the earlier generation except that a triclinic feldspar, probably andesine, now appears as an independent constituent. Quartz, biotite and muscovite constitute the other essentials. Large but relatively few individuals of magnetite, titanite, apatite and zircon are accessory. The quartz and feldspars are roughly equidimensional with diameters becoming as much as a centimeter in length; in fact the feldspars are often transitional into the phenocrysts. Quartz very often crystallized simultaneously with the feldspars resulting in the formation of a true micropegmatite which is extremely common in slides of the granite from all the areas. It is best shown in specimens collected along the railroad from Hinsdale to Ashuelot. There can be little doubt that the structure is primary in the formation as a whole. It is possible, however, that in zones of stress the development of the structure has been aided by the metamorphic cause of crushing, as described by Howitt, Hobbs and other writers.

The proportions of phenocrysts to matrix and of acid to basic constituents are quite constant in the porphyritic granite. The latter relation is that usually found in most highly acid granites. Now and then, a well-foliated segregational mass of biotite, quartz, much titanite and apatite, wrapping about phenocrystic cores of feldspar, may be encountered. Again, a phase of the rock nearly devoid of phenocrysts is not rare, although quantitatively it is insignificant as compared with the porphyritic phase. Both of these variations from the type will be discussed in what follows.

Field relations: The Winnipiseogee area.—The general distribution of the porphyritic granite in the Winnipiseogee area is described at length in "The Geology of New Hampshire."[1]

The topography of the area is, on the whole, not of a very definite nature. The greater reliefs, which vary from 800 to 1500 feet above sea level, are without distinct trends, and are the forms which might be expected as the result of eroding a massive rock of pronounced homogeneity. Upon this rolling ground the glacial drift has been deposited in unusual thickness, especially in the southern half of the area, where the hills are commonly composed of washed drift and till. Correlative with glacial reliefs are the glacial depressions seen in the numerous lakes and ponds which make such picturesque variety in the landscape of Carroll county. These modern deposits make it difficult to work out the relations of the bed-rocks. The variety of outcrops in many parts renders the determination of contact lines almost impossible, and it is largely to this cause that the suppositional nature of some of them is due.

The geological relations of the Winnipiseogee area.—The survey map places the porphyritic granite of this area in contact with the Lake Winnipiseogee gneiss, the Montalban group of schists, the Rockingham mica-schist, and the various eruptive masses of Waterville. For convenience we shall briefly indicate

[1] Vol. II, p. 592.

the facts of field observation which have been adduced in connection with each of these formations.

The porphyritic granite in contact with the Lake Winnipiseogee gneiss.—Close by Gilford Station, on Smith's Neck, the boundary line of the porphyritic granite and the Winnipiseogee gneiss appears, and, so far as known, this is its most southerly extension in this district. It is a typical acid biotite-gneiss at this place, elsewhere muscovite may be found. A few of the outcrops are significant. Here and there in the porphyritic granite masses of rock very similar to the main body of the schist occur in a horselike relation, although nowhere could the actual contact be found, and thus render possible a proof of that derivation of the masses. On Governor's Island, two miles to the westward, a large outcropping of a coarse muscovite-biotite-gneiss occurs. This is a typical representative of the Lake Winnipiseogee gneiss, and this mass is completely surrounded by porphyritic granite for a distance of at least a quarter of a mile in all directions. About that distance from this outcrop of schist, the real contact of the porphyritic granite and Lake Winnipiseogee gneiss was found, and it became evident that in the first occurrence we had to deal with an outlier removed by some means from the parent schist terrane. This relation could hardly be explained except on a hypothesis of the igneous intrusion of the coarser rock in which the schist was enclosed as a great horse. The truth of this supposition was strengthened by the discovery of two marked apophyses of the porphyritic granite running into the inclusion. Returning to the molar contact, a corroboration of our conclusion from a study of the outlier appears in a clearly defined tongue of the porphyritic granite which can be traced for some distance into the schist. Whereas on Smith's Neck the porphyritic granite was largely granitic, here a well-defined foliation characterizes the rock. The strike of the foliation planes is N. 3° E., and the dip is 82° to the east. It is noteworthy that the strike and dip of the schistosity in the adjacent schist is the same. In other words, there is an apparent conformity between them. At several places among the numerous outcrops of porphyritic granite on the island, very coarse pegmatitic dikes appear which are similar to the granite, and do not appear to belong to the class of pegmatite veins of segregational origin so common in the crystalline area of the state.

About a mile and three-quarters from Weirs there is a small inlet, on the south side of which the porphyritic granite is in contact with a dark coarse-grained gneiss. This seems to be equivalent to the Lake Winnipiseogee gneiss. It is cut by an apophysis of the porphyritic granite, and a horse of the schist can be seen on the bare ledges enclosed within the other rock. Again, as on Governor's Island, there is an apparent conformity of position.

Just across Meredith Bay, on Spindle point, an interesting contact occurs. The porphyritic granite outcrops occasionally on and about the road from Meredith with pretty definite foliation, the strike varying from N. 20° E. to N. 40° E., the dip high, but changing from easterly to westerly in an irregular fashion. On the top of the hill at which the road ends, an solated mass of another rock is conspicuously displayed in the well-smoothed ledges. It is dikelike in its form, being fully four hundred yards long and from ten to twenty wide. There is a distinct schistosity with its planes parallel to the longer axis of the mass which strikes S. 40° W. The dip is high at about 75° to the southeast, making an apparent conformity with the enclosing porphyritic granite, which is here well foliated. Within a distance of 300 yards south of this long band, and oriented with the longer axis parallel to it, smaller bodies of the same rock occur, again completely enclosed by porphyritic granite. They have the same pronounced structure-planes with a similar relation to the foliation of the country rock. From the hill top the largest of all these parallel bodies strikes toward a larger body of the same rock. Like the other, this mass is characterized by a strong gneissic structure. It also possesses an elongated form. We have here to deal with a number of horses immersed in a once molten magma which chrystallized out as porphyritic granite. The patent differences of grain and structure, the sharp boundary between the two rocks, the irregular thinning and thickening along the length of the inclusions, all point to this belief. Here and there, within their boundaries, obscure apophysal extensions of the coarser rock may be observed. But this conclusion reaches practical certainty when the molar contact of the porphyritic granite and the "Lake Winnipiseogee gneiss" is studied. The latter is seen to be precisely the same coarse-grained biotite-gneiss as that in the inclusions, except for certain differences which can be explained as due to exomorphic change wrought by the porphyritic granite. Apophyses of the latter may be seen at the neck or isthmus of the peninsula cutting the gneiss. An important relation subsists between this line and the arrangement of horses on the hill. Not only are they parallel to one another, but they lie parallel to the line of molar contact.

Transition zone at Centre Harbor.—At Centre Harbor the gneiss lies on the east side of the boundary and at some distance from it is the usual coarse-grained muscovite-biotite rock of the Lake Winnipiseogee gneiss terrane. Its foliation planes strike N. 15° W., and the dip is about 60° easterly. As one approaches undoubted porphyritic granite through a distance of fifteen feet from the contact, one notes the large orthoclase and microcline feldspars two inches long, which normally are confined to the porphyritic granite, now scattered through the finer-grained rock with their longer axis parallel to its schistosity. They grow more numerous as the porphyritic granite is neared, until finally some four or five yards from their first appearance, the outcropping rock is typical porphyritic granite. It possesses the same strike and dip as the gneiss, being well foliated. There is thus a complete and slow graduation of the one terrane into the other, making it impossible to draw any line between them.

Transition zone near New Hampton Station.—A similar zone of transition between these two terranes occurs a mile and a quarter from New Hampton Station on the road running southeast from the station. The zone of passage is here much wider than at Centre Harbor, but the properties of its magmalike gneiss with the sprinkling of large porphyritic crystals of feldspar are identical with those of the other locality. As a rule, there is a sharp contact between the porphyritic granite and the invaded rocks, like that which in general characterizes plutonic bodies. These belts of transition have at first sight a puzzling appearance. That they are, in reality, eruptive contacts seems, however, to be unquestionable. Durocher long ago noted such an intimate union along the boundary of gneiss cut by stock-granite. He considered the temperature of the igneous rock in such instances sufficiently high to produce a melting up of the gneiss the "particules" of which "ont dû posséder une assez grande mobilité, et cristalliser à peu près dans les mêmes conditions que les molécules du magma granitiques.[1] In his "Geog. Beschreibung Bayerns,"[2] Gümbel speaks of there being numerous transitions from "bunter gneiss" to "bunter granit" which cuts the former. Michel-Lévy has very clearly discussed the phenomenon in general. He says:[3] "C'est ici le cas de remarquer que lorsque deux grandes masses de roches acides se touchent, le plus souvent elles se trouvent réunies par une zone de passage plus ou moins puissante, dans laquelle les caractéres pétrographiques des deux roches sont, pour ainsi dire, confondus et mélangés.[4] In the same paper from which this quotation has been taken, the author cites many examples of such transition, among which that from granite to gneiss[5] and that from granite to "micro-granulite" may be especially mentioned. He explains them as due to an impregnation of the older rock by "les éléments fluides en voie de dégagement" from the igneous rock. When the temperature and pressure are suitable, a part of the constituents of the older rock will become mobile and will tend to assume the same structure as those of the second period of consolidation in the younger rock.

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[1] Mém, de la Soc. Géol. de France, 2e sér. t. VI, p. 47.

[2] Abtheil. II, p. 272.

[3] Bull. de la Soc. Géol. de France, 3e sér., t. VII, 1878-9, p. 852.

[4] Cf. Ch. Vélain, Conférences de Petrographie. Paris, 1889, p. 6.

[5] Cf. LEHMANN, Untersuch. über die Ent. der alt. kryst. Schiefergesteine, p. 76. GREGORY, Q. J. Geol. Soc., 1894, p. 260 ff. BARROW has noted a complete amalgamation at the contact of granitite and diorite, of which the former is the intrusive member, Q. J. Geol. Soc., 1892, p. 121.

McMahon pointed out how difficult it was to explain the presence of zones of transition about the Dalhousie granite of the Himalayas in some places and their absence in others on the old metamorphic theory of the central gneiss. He favored the opinion that, whether a zone of passage characterizes the contact or not, depends on the closeness of mineralogical similarity between the Dalhousie granite and the invaded strata. Only in places where the latter had been regionally metamorphosed did he find the appearance of gradual change from the granite into the country rock. The transition zone described by Lawson between the Laurentian gneiss and hornblende-schist in Rainy Lake region is so similar to the zones of the porphyritic granite that it will be well to read his own words on the subject: "Within the hornblende-schist, distinctly recognizable as such, there may occasionally be detected large crystals of red feldspar, which is quite foreign to these rocks, as if the feldspathic magmas had penetrated within the schist and crystallized there in the same large crystals in which they are wont to appear in the coarse gneiss."[1]

These authentic determinations of transgressive junctions between plainly eruptive rocks and their respective country rocks, coupled with the expectation that they should appear in contacts of that nature, lead us to follow Gregory[2] in concluding that they may form a useful criterion for a decision on an eruptive origin for massive rocks. So far as this principle is concerned then, the porphyritic granite can be eruptive.

The foregoing description of contact phenomena seems to us to indicate that the porphyritic granite has been intruded into the schistose rocks which have been grouped together in the terrane of the Lake Winnipiseogee gneiss by the survey. This conclusion is forced upon one as well in the study of the northern extension of the "fishhook" as in the southern part to which attention has been so far called.

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[1] Ann. Rep. Geol. Surv. Canada, 1887–8, Part. F. p. 33.

[2] Q. J. Geol. Soc., 1894, p. 262.

The porphyritic granite in contact with the Montalban group of schists.—We shall not consider in this place the grounds on which the survey has separated the Lake Winnipiseogee gneiss from the Montalban group. Our field observations have shown us pretty clearly that, although the lithological characters of the two terranes may be on the whole different, any distinction between them from a supposed difference of age is as yet without demonstration. Be this as it may, the problem before us can be solved without either proof or disproof of such a contention. At many points along the contact, the schists of the Montalban group are intersected by apophyses from the porphyritic granite, and appear as inclusions in the latter rock. The evidences of an intrusive origin for the porphyritic granite are of the same nature as in the case of the Lake Winnipiseogee gneiss, and are just as conclusive.

The Montalban group and porphyritic granite come in contact along the line running from Long Bay to Great Bay, and about one half mile east of Great Bay. Here a number of well-marked horses of the neighboring Montalban gneisses occur in the porphyritic granite. They possess a thoroughly gneissic structure, being as well foliated as their parent mass less than a hundred yards away. In this case the horses are not elongated and do not show any definite relation of position, either to one another or to the main contact line. Apophyses of porphyritic granite were also discovered along this part of the boundary.

An interesting occurrence of the gneiss appears in the road on the north side of Shaw's hill. It is isolated and completely surrounded by porphyritic granite whose nearest molar contact is nearly a mile away. This great horse is highly schistose, and several tongues of the granite here and there cut across the structure planes. The development of garnets in the horse may hint at some degree of contact metamorphism.

A second large horse which is some distance from its parent terrane outcrops one mile and a half north of Holderness on the upper road. Here a gigantic slice of the country rock, about sixty feet wide and three hundred feet long, has been floated off and rests with its longer axis north and south, *i. e.*, parallel to the molar contact. It is composed of the usual biotite gneiss in which a thick sheet of hornblende-gneiss lies embedded, making up most of its mass. The latter has itself the appearance of being an eruptive rock which is thus older than the porphyritic granite. Associated with it are a large number of smaller biotite gneiss fragments which have no definite arrangement, but make a confused medley of discreet masses in the porphyritic rock. The whole looks like a huge flow breccia. Rather more than a half mile further north on the same road, there is a breccialike aggregation very similar to the last, even to its containing hornblende-gneiss folded up in a large mass of biotite-gneiss.

Three hundred yards west of where Dr. Dana's road leaves the four corners at New Hampton Centre we note another of those zones of transition between the porphyritic granite and the schists in contact with it. It is some twenty feet wide, and is strikingly similar in appearance to the case already described at Centre Harbor. Here the schist is cut by intrusive tongues with more or less sharp boundaries. These apophyses run across the gneissic planes.

On the extreme eastern end of the Sandwich Mountains at an elevation of about seven hundred feet above the Bear Camp River, a remarkable flow breccia or "permeation area"[1] outcrops in some extensive pasture fields. The rock presents all the features of a plutonic flow. The horses are here almost entirely hornblende-gneiss, some of them massive, both fine-grained and coarse-grained, others distinctly schistose. The porphyritic granite is on the whole granitic in appearance, but at the boundaries of the fragments, the feldspar phenocrysts are often oriented about them in a way which is strongly suggestive of a flow structure. The usual trendless nature of its constituents is also lost in some of the tongues of porphyritic granite which penetrate the fragments in all directions. There the minerals are pulled out in planes parallel to the walls of the intrusion. The source of the hornblendic inclusions was discovered within a hundred yards of the breccia. An unknown thickness of the hornblende-gneiss lies interbedded in the biotite-gneiss. This great breccia outcrops at several places through a distance of three hundred yards along the base of the mountain and is only one hundred yards from the massive terrane of the Montalban group, which is continuous all the way from Morgan Mountain.

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[1] Barrow, Q. J. Geol. Soc., 1893, p. 331.

These occurrences of hornblende-gneiss in the porphyritic granite throw light upon the "hornblende rock" which was noted by Hitchcock in the Survey Report[1] as occurring to the east of Wickwas Pond. It covers altogether about an acre in extent. The rock is a hornblende-gneiss closely related in composition to the masses already described. It has a strong schistosity which lies parallel to the foliation of the granite enclosing it. The latter sends intrusive tongues into the gneiss which is evidently a large floe of the country rock moved far from its original source.

The small oval area of the porphyritic granite on the top of Mount Prospect is a stocklike body which suggests from its position an intrusive origin. Field study confirms this opinion. The rock is typical of the porphyritic granite in composition, in grain, and in the size of the phenocrysts. Within this porphyritic granite there are embedded several horses of the surrounding Montalban schists. The latter are extensively crumpled, perhaps by the intensity of the granitic intrusion. Again one can notice the parallelism of the phenocrysts to the margins.

The porphyritic granite in contact with the Rockingham mica-schist.—One of the most important localities in the state to suggest an intrusive origin for the porphyritic granite is on Saddle Hill, where that rock comes in contact with the Rockingham mica-schist. Here the formation is composed of well-foliated, fine-grained, muscovite-biotite-schist with abundant mica. The molar contact is found on the eastern end of the hill. It strikes N. 25° W., and is parallel to the schistosity of the mica-schist and to the pronounced foliation of the porphyritic granite. All the structure planes dip westward at a high angle. Going across the strike from the contact toward the porphyritic granite a remarkable series of elongated horses of the schist interrupt the continuity of the granite. They are usually much longer than their width, as, for example, a large one 150 feet long by 35 feet wide, which appears on the west side of the saddle. In most cases there is a definite orientation of the horses parallel to the contact line, while the foliation of the porphyritic granite wraps around the inclusion in a significant way. They are uniformly schistose with that structure as well developed as in the main body. Crumpling of the horses is also characteristic. For about two hundred yards east of the contact, the schist is cut by several intercalated sheets of porphyritic granite, varying from five to ten yards in thickness. Their phenocrystic feldspars lie parallel to the walls between which the sills were intruded. Similar sheets can be found in the pasture on the southern flank of the hill and west of Randlett Pond.

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[1] Vol. II, p. 594.

Relation of the porphyritic granite to the Waterville eruptives.— It is probable that the porphyritic granite is older than all of the intrusive rocks of the Waterville Mountains. The contacts were discovered in only one place, namely, on the southern slope of Mount Whiteface; there the hornblende-granite composing the mountain distinctly cuts the porphyritic granite. In the path from the Elliott House, at Waterville, to the top of the Sandwich Dome, many outcrops of several types of granitic rocks present a problem of correlation which the writer has had no opportunity to solve. It is possible that these rocks are chilled phases of the Conway granite; for there is, in the main, a tendency towards a porphyritic structure throughout, which on the one hand becomes more pronounced as one approaches the porphyritic granite, and is entirely lost in the very coarse Conway (hornblende) granite in the bed of the Mad River. If this hypothesis be correct, the Conway granite is younger than the porphyritic granite, for at about 1800 feet above the river the porphyritic phase distinctly cuts the coarser rock.

The Ashuelot area.—The country rock about the porphyritic granite of the Ashuelot area is referred by the survey to three different formations. the Bethlehem gneiss, the schists of the Coös group and the Montalban group. Specific reference to this area was made in the second volume of the Survey Report.[3] In their general correlation, the survey considered the markedly oval form of this and other occurrences of the porphyritic granite as allying it in point of age to similarly shaped masses in the Archæan elsewhere. Such a form has a nearer homologue to the batholites described by Emerson in western Massachusetts, and as we shall see, these similar forms have similar origins. That the porphyritic granite of the Ashuelot area is eruptive and of an intrusive nature can be amply proved. We shall not attempt to trace the evidence from the contact-phenomena, as it might be traced in a complete description of the whole boundary. It is of the same nature as that outlined for the Winnipiseogee area. With that fact in mind, we have considered it expedient to refer to a few only of the possible localities which can be readily visited for confirmation of our views.

A representative contact of the porphyritic granite and Coös mica-schist outcrops where the boundary line between them crosses the road running southwest from Ashuelot over Gun Mountain. Here and along the western ridge of Gun Mountain the typical biotite-muscovite-schist is strongly charged with interbedded actinolite-schist and quartzite. Several apophyses of the porphyritic granite cut the schist. One of them, twenty feet wide, cuts across the strike, extending a considerable distance from the contact before it disappears under the soil-cap; another over two feet in width is also well exposed, but lies nearly in the planes of schistosity. Horses of schist are embedded in the granite, but the overlying loose deposits prevent the discovery of any definite arrangement among them. The granite itself has a good parallel structure, and it is important to note that its structure-planes are conformable in strike and dip with those of the adjacent schists. This same conformity was several times observed along this western side of the area. Sometimes, even at the contact, the porphyritic granite is quite granitic without a trace of the foliated structure. A good example of this appears at the contact on Hall's hill, near Chesterfield factory. At this locality, too, there is no doubt as to the relation of the two formations. The intrusive tongues of porphyritic granite cut across the schists and associated gneissic bands in a very marked way; the sharp contrast of grain and composition enabling one easily to differentiate the igneous masses. Occasionally dikes of the porphyritic granite may be found traversing the schists at a distance from the contact. At the three corners, about a mile south of Chesterfield, numerous great veins of coarse pegmatite outcrop and with them occurs a set of true porphyritic granite dikes which are probably apophyses of the main mass, half a mile away.

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[3] P. 470.

Facts of like character refer to the contact with the Bethlehem gneiss on the eastern side of the oval. Field evidence shows that the latter is of the same metamorphic epoch to which the Coös mica-schist is referred; thus, the argument regarding the better exposed part of the boundary applies to it in its entirety.

Fitzwilliam area.—We have seen already that the survey suspected an eruptive origin for certain parts of the porphyritic granite, and had cited facts from the Fitzwilliam area as in part the basis for the conception. The contact line of this little patch of the rock is very clear in its teaching. Even more graphic than that of the bowlders described in the survey report[1] is the evidence where the rock is in place. About a mile southwest of the village the porphyritic granite is found in a pasture field by the roadside. Included in it are many horses of biotite-gneiss, some of which are large, being as much as twenty-five feet in diameter. Within one of the latter an interesting irregular injection of the porphyritic granite is well exposed. One feature exceptionally well shown is the fine-graining along the margins. At this place, too, dikes of the Concord granite cut the porphyritic granite, and the former rock is thus the youngest terrane in the region. Since it surrounds the porphyritic granite on all sides, this Fitzwilliam occurrence may itself be a large floe brought up from below from a much larger mass.

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[1] Vol. II, p. 471.

The Main area.—Our observations on the Main area were extended only to its southern half. The great thickness of the various glacial deposits make it, on the whole, less satisfactory for a study of contact relations than the Winnipiseogee area. We have aimed in the course of a somewhat hasty examination to discuss the facts as regards the schists grouped by the survey under the names of the "Ferruginous slates," and the "Ferruginous schists." In both, the rocks consist of two-mica-schists, biotite-schist, biotite-gneiss, and muscovite-biotite-gneiss, all of which may be garnetiferous. Between them we can trace no definite distinction, either of composition or of age, and the area on the eastern border, marked "Lake Winnipiseogee gneiss," encloses stripes of schistose rocks which are identical with those of the above-mentioned groups. Here, as often elsewhere, the grounds for the subdivision carried out by the survey do not appear in the field.

The great sill of porphyritic granite to the north and northeast of Greenfield has one contact well exposed with interruptions for the distance of a mile. It is an intrusive one. The granite was erupted into the schists along a plane of foliation, and there is the usual development of parallel structure in many of its outcrops which accords with that of the walls. The intrusion is, on the whole, sheet-like in its form, though in some places where the schists are intensely folded, it cuts across their structure-planes. In such cases the foliation of the porphyritic granite remains parallel to the boundary line. The apophyses penetrate the schists irregularly in all directions, generally paying no attention to planes of weakness. They are finer-grained than their parent sill, but show here and there a feldspar as much as two inches in length.

One of the most interesting parts of the contacts is that which belongs to the area marked "Lake Winnipiseogee gneiss" by the survey in the towns of Antrim and Hillsboro. It is exceptionally well exposed at intervals for a distance of five miles, and especially on the long ridge some two miles west of Antrim. The name thus given the rock with which the porphyritic granite here comes in contact is a decided misnomer. The new terrane consists of an ancient metamorphosed eruptive cutting the "Ferruginous" rocks in every way similar to the schists that extend from Bennington to Henniker. This complex is itself cut by the porphyritic granite.

The older eruptive rock is a typical coarse granitite containing a good deal of muscovite which is all secondary. The quartz is the common blue variety of New Hampshire crystallines. Both orthoclase and a basic plagioclase occur, but they are generally badly decomposed. It is a difficult rock to diagnose thoroughly on account of the vast amount of crushing which appears in the thin section. The quartz and feldspars are much granulated marginally, the unbroken cores showing the characteristic wavy extinction. The plagioclase lamellæ are often bent through large angles. Minute faulting is common in them, and throughout the slides the shreds of biotite are bent and twisted in a striking manner, while the extinction on the base of biotite plates is most irregular. In fact the condition of this rock is in marked contrast with that of the porphyritic granite close by. The granite is quite without any signs of serious disturbance; the granitite has endured the very severe mechanical strain of extensive mountain-building. Often the signs of developed schistosity in this once massive rock are easy to discern in the ledges, and these new structure planes strike a few degrees east of north, *i. e.*, they lie in the main parallel to the strike of the "Ferruginous" terrane.

Now, within the crushed granitite there is an extraordinary display of inclusions, varying in size from small fragments to masses twenty feet square, all of which have evidently been derived from the older schists to which they are mineralogically and structurally similar. These horses are highly ferruginous, and weather with the same rusty appearance that characterizes the parent rock. So great is their number in some places that considerable stretches are veritable flow breccias. But it is rather the remarkable crumpling and other evidences of intense folding which attract one's attention to these outcrops. The sliverlike horses are very often bent into sigmoid flexures; sometimes one is seen to be completely doubled back on itself in a nearly closed fold. They are usually much jointed, and here and there actual movement along a fault plane may throw one part of the inclusion a foot or more out of its normal continuity. While there is not much difference mineralogically between these inclusions and the rock of the ferruginous terrane, yet there is some evidence of a metamorphic change due to the granitite. About one of them, some two feet long and a foot and a half broad, in particular, a two-inch zone filled with large biotites was developed. The biotite of the granitite itself is often segregated in large individuals. Many of the horses have been considerably melted up, and it is probably the absorption in this way of so much of the iron oxides that conditions the characteristic deep reddish brown color of the weathered granitite.

This terrane has but few affinities with the simple Lake Winnipiseogee mica-gneisses, where they occur in their normal fresh uncrushed habit. No evidence is yet forthcoming that the latter are eruptive. Not only do these multitudinous horses prove the eruptive origin for the granitite, but its actual contact with the ferruginous schists was found on Riley Mountain, and it tells the same story. The usual field criteria of the presence of horses, apophyses, and intrusive sheets are there exhibited. A rock zone of the foregoing description, averaging rather more than a quarter of a mile in width, runs southward five miles to the Antrim ridge above mentioned, always appearing between the porphyritic granite and the main body of schists.

At many places along its western margin the porphyritic granite cuts the granitite, but often passing into it by a zone of transition analogous to those described in the Winnipiseogee area. Thus we have added another to the crystalline terranes which have been profoundly affected by dynamic processes since their formation; they are in this respect to be contrasted with the younger relatively unaltered porphyritic granite, and lastly, they are of interest not only from their relation to the history of igneous activity in the state, but also from the light that they throw on the age and origin of the granite.

REGINALD ALDWORTH DALY.

STUDIES IN THE SO-CALLED PORPHYRITIC GNEISS OF NEW HAMPSHIRE. II.

Contact Metamorphism.— The endomorphic changes wrought by the granite intrusions are relatively slight. Thus the biotite-gneiss and hornblende-gneiss southwest of Lake Wakawan have the same mineralogical composition at the contact as they have a quarter of a mile away from it along the strike. On Spindle Point, gneisses of like nature show the only exomorphic change discovered throughout the whole terrane of the Lake Winnipiseogee gneiss. Yet even this is a doubtful case, since the only evidence is the presence of some sillimanite needles and a few garnets in the schist near the granite. Again, the interbedded biotite-gneiss, muscovite-biotite-gneiss, and actinolite-gneiss, at the outlet of Little Squam Lake, are practically unaffected by the granite. The same is true of the large biotite-gneiss-inclusion on the north side of Beech Hill, as well as of the whole contact-line of the Montalban group.

The schists on Saddle Hill exhibit the best metamorphic belt which appears in the Winnipiseogee area. Specimens of the country-rock were taken at localities from one to eight hundred feet from the contact, and in all of them the country-rock proves to be a typical muscovite-biotite-schist with accessory sillimanite in long needles. Inside that zone toward the granite, however, a pronounced metamorphic aureole encloses phases of the terrane which represent important modifications of the schist. One of them, some eighty feet from the contact, is a hornfels largely made up of zoisite and andalusite (?) with quartz and magnetite. Another, four feet from the granite, is a compact mica-schist richly charged with garnets; while within five inches of the contact this garnetiferous schist has absorbed a large amount of orthoclase and plagioclase which seem to have been derived from the neighboring granite.

The Ashuelot area is even more nearly devoid of distinct zones of contact-alteration. Several suites of specimens were taken across the marginal belt of schists at several different localities, but in none of them was a definite alteration of mineral content observable, as one goes toward the igneous rock. While the Coös schists are highly garnetiferous at the contact, they are often just as metamorphic in habit a mile or more from the granite. Interlaminated actinolite-schists are abundant among the common mica-schists of the area. They show no change at the contact. The Bethlehem gneiss is often garnetiferous, and in some slides the garnets are seen to be larger and more idiomorphic near the granite than away from it. Apart from this fact, one would not suspect from an inspection of the marginal alterations that the porphyritic granite was once an igneous body intruded in these same rocks in a molten state.

Finally, it would be difficult to point to any particular part of the Main area as exhibiting metamorphic phases in the schistose country-rock of the porphyritic granite which could not have been produced before the granite was erupted. One hundred and fifty feet from the great Greenfield sheet a typical quartz-garnet-hornfels can be found, but from that rock to the granite one passes over the typical biotite-muscovite-schist of the region. The latter itself may be garnetiferous. It does not, however, differ from similar phases of the ferruginous rocks several miles from the contact. North of Henniker there outcrops another hornfels at a contact with a prophyritic granite apophys~~is~~ and about 50 feet from the molar contact. It is a compact aggregate of quartz and garnet with a large admixture of a colorless pyroxene and a little accessory plagioclase and muscovite. Notwithstanding this kind of association, these and other examples cannot as yet with safety be considered as contact phases, nor do they afford positive evidence of an eruptive origin for the porphyritic granite.

The small amount of exomorphic change in the contact-belt is that which might be expected from the conditions of the eruptions. It is well known that, other things being equal, acidic igneous rocks are less likely to be altered by intrusive masses than are the more basic rocks. In the same way sedimentary rocks are in general more susceptible to contact metamorphism than the crystalline chists or than igneous rocks.[1] Pohlig noted important differential effects of the trachyte in the Siebengebirge. Fragments of gneiss enclosed in the eruptive rock were relatively unchanged as compared with inclusions of clay-slate in which andalusite and other metamorphic minerals were developed.[2] Lehmann has described granulite inclusions in the granite of Markersdorf which he found to be entirely unchanged by the granite.[3] No student of contact-belts needs, however, to be reminded that in them there is pronounced selective metamorphism depending upon the nature of the rocks invaded. Those which have advanced furthest in the direction of mineralogical stability will usually be the rocks which are least altered. If, thén, there had been regional metamorphism of the country-rock before a given intrusion occurred, such terranes will tend to be without distinct zones of alteration. Such is the case with the New Hampshire rocks. In the sequel the chief evidence for this conclusion will be given, but we can anticipate somewhat by stating the fact that the same series of schists which are cut by the porphyritic granite are just as thoroughly crystalline many miles from the porphyritic granite as they are in its immediate vicinity. Moreover, they attained this crystalline character in the process of mountain-building and not by any kind of local thermo metamorphism induced by underlying areas of the porphyritic granite.[4] The eminent schistosity of these rocks was anterior to the granitic intrusion, and it is an effect concomitant with the recrystallization. Thus it was a series of terranes already regionally metamorphosed that were cut by the porphyritic granite. They had reached a state of approximate mineralogical equilibrium and but little rearrangement of the constituent elements was possible by mere contact action.

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[1] Cf. HUDLESTON, Address Pres. Geol. Soc., 1894; Q. J. Geol. Soc., p. 121.

[2] Tschermak's Mitth., 1880–1, p. 353.

[3] Untersuch. über die Entsteh., der altkryst. Schiefergesteine, 1884, p. 7.

[4] Cf. BARROW, Q. J. Geol. Soc., 1893, p. 352.

Moreover, at Fitzwilliam, where the inclusions of the neighboring biotite-gneiss are extremely well exposed, there does not seem to be the slightest change in the horses. Yet there can be no doubt that the porphyritic granite is here distinctly eruptive in the gneiss. In the same way, the ancient granitite described on the west and northwest of the village of Antrim has produced no material alteration in the composition of the schist inclusions, for in that feature they are identical with their parent terrane for several miles from the contact.

It seems reasonable, then, to conclude from the brief account of exomorphic contact-phenomena just given that they do not invalidate the argument for the porphyritic granite's being eruptive. It means that the conditions were not such as to permit of the development of the well-marked metamorphic aureoles which one might expect in invaded terranes composed of relatively unaltered rocks.

Endomorphic changes.— More often than not where the actual contact between the porphyrictic granite and the older formations appears, there is practically little change either in the composition or grain of the granite. This fact is characteristic of apophyses as well as of the main body. In the Winnipiseogee and Main areas particularly, the feldspar phenocrysts and their matrix are remarkably persistent in the size of individual minerals. The reader will remember that a broad band of the porphyritic granite with rare phenocrysts appears on the western side of the Ashuelot area, and again that, on the eastern side, there is evidence of fine-graining in the Bethlehem gneiss-contact which can hardly be explained except as belonging to a chilled phase of the igneous rock. It is true, however, that this phenomenon is, on the whole, rather the exception than the rule in the different areas. We cannot but think that the invaded schists must have been at a high temperature themselves when the granite was intruded. Witness the widespread zones of passage between the two. The great coarseness of the matrix shows that the granite was long in crystallizing and in that process would naturally lose much heat to the surrounding rocks.

Thus the latter could not in the final stage of consolidation cause a serious differential cooling in the marginal part of the granitic magma. That there was some influence exerted upon the igneous rock is indisputable. Almost universally thin sections of the contact-zone exhibit a very marked granophyric intergrowth of the quartz and feldspar of the matrix. This micrographic development is quite independent of that noted as common about the phenocrysts, and is quantitatively much superior in value to the latter. The occurrence of the graphic structure in the matrix is usually restricted to the contact-zone of not more than a few inches or feet in width. It is noteworthy, however, that in parts of the Ashuelot area where there are evidences of some crushing, this structure is found in various parts of the coarse matrix, though far from a contact. It doubtless originated as a result of rearrangement during the period of stress which the rock has here undergone.

The origin of the foliation in the porphyritic granite.—It is now well established that gneisses may belong to three classes which in the words of Gregory[1] may be named metapyrigen-gneisses, clastic-gneisses, and fluxion-gneisses. The first kind is produced by the pressure-metamorphism of igneous rocks, the second by the complete alteration of sediments. The third division has its origin in molten rock-magmas which have undergone "fluxional movements anterior to complete consolidation in a mass not perfectly homogeneous."[2] The porphyritic granite of New Hampshire owes its foliated structure to the same cause as that of fluxion-gneisses. In short, this porphyritic gneiss is a porphyritic granite with a flow-structure. The parallelism among the constituents was assumed when the rock was not yet fully crystallized out and cannot thus be referred to any metamorphic result of mountain-building acting on an already solidified mass. It is a primary structure. Since this fact is not as yet demonstrated in what has been said, and since we are dealing with a great terrane characterized everywhere by this foliation which has been the subject of serious misapprehension among early investigators in the state, we shall go into some detail to establish this position.

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[1] Q. J. Geol. Soc., 1894, p. 266.

[2] T. G. BONNEY, Some Notes on Gneiss, Geol. Mag., 1894, p. 118. Cf. HILL and BONNEY, Q. J. Geol. Soc., 1892, p. 137.

It was not until the next generation after von Buch[1] described flow-structure in lavas that the phenomenon was studied with reference to the origin of gneisses. Scrope[2] in 1840 and Darwin[3] in 1844, closely followed by Naumann,[4] first laid emphasis on the truth that "dragging movements" on a cooling granitic magma may lead to the formation of gneiss. Since that time, a host of observations have confirmed their idea so completely that it is now possible to frame the most important criteria which ought to be applied to a problematical case, and, if satisfied, should enforce belief in the gneissic structure of that particular instance being of fluxional origin. It is proposed to consider briefly these criteria with respect to their validity and to their relation to our particular problem.

1. Since the fluxion-structure is due to differential stress, we should expect some parts of a mass, to display a greater excellence of the foliation than others. There will be zones of relatively rapid movement and zones of more static conditions; at least during the geological movement of final consolidation. Thus, we may expect to find transitions from trendless granite to well-foliated granite or gneiss.[5] We have already seen how abundantly this change is exemplified in all the areas of the porphyritic granite. Both of the State Surveys noted this relation between the massive and foliated phases.[6] The earlier one seized upon the former as indicating simply a granite, the second

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[1] Geognost. Beobacht. auf Reisen durch Deutschland und Italien, 1809, II, p. 209.

[2] Trans. Geol. Soc., 2d ser., II, p. 228.

[3] Geological Observations, etc., 1st ed., 1844, ch. iii.

[4] Neu. Jahrb., 1847, p. 297. Q. J. Geol. Soc., Notices of Memoirs, p. 1.

[5] MICHEL LÉVY, Bull. Soc. Geol. de France, 1878–9, p. 852. MCMAHON, The Gneissose-Granite of the Himalayas. Geol. Mag., 1887, p. 214. *Ibid.*, 1888, p. 63. HARKER and MARR, The Shap Granite, etc. Q. J. Geol. Soc., 1891, XLVII, p. 284 EMERSON, Bull. Geol. Soc. Am., I, 1890, p. 559.

[6] Note, Geol. of New Hampshire, Vol. II, p. 99.

survey regarded the non-foliated parts as fused parts of a series of altered sediments.

2. The parallel structure ought to be best assumed along the contact, because there the essential condition of an appropriate viscidity will be assumed within a zone which has a dominant trend. Where the interaction effects of more than two cooling surfaces meet, as they do in a mass of considerable breadth, there is a tendency towards the obliteration of parallelism induced in any one zone of chilling at a plane of contact. Convection currents will further complicate the flow-structure and to a greater extent in the hotter core of an intrusive mass than in the chilled zone. For these reasons parallelism among the constituent minerals should be most clearly exhibited along the boundaries where the structure-planes of the igneous mass will accord in direction with the plane of contact. The central area may either lose any incipient foliation or show sudden irregular changes of strike and dip of fluxional planes which do exist. In other words, wherever else it may appear, the fluxional structure is to be looked for chiefly at the margins.[1]

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[1] BRÖGGER (Die Silurischen Etagen 2 und 3; Kristiania, 1882, pp. 325, 326), describes the endomorphic zone of contact of his granitic and syenitic eruptives as possessing a parallel structure "wodurch gestreifte Gesteine, bisweilen wie echte krystallinische Schiefer aussehen. It is parallel to the irregular boundaries of the igneous rocks.

MCMAHON, Note on the Foliation of the Lizard Gabbro; Geol. Mag., 1887, p. 76.

BARROIS states that in the granulites of Morbihan the parallelism is most perfect when the contact-line is in the strike of the enclosing strata. In such parallel contacts, the granulite is apt to change to a "granulite porphyroïde, à grands éléments, alignés fluidalement." In "contacts perpendiculaires" the rock has an aplitic phase in which the crystalline constituents have regular geometric forms. He considers that such differences in the intruded granite depend on the country-rock as an agent chemically inactive but "diversement conducteur de la chaleur et de la pression." Sur les modifications endomorphes des massifs granulitiques du Morbihan; Comptes Rendus, CVI, 1888, p. 428.

GEIKIE, A., The History of Volcanic Action during the Tertiary Period in the British Isles; Trans. Roy. Soc. Edin., 1888, p. 37.

BARLOW, On the Contact of the Huronian and Laurentian Rocks North of Lake Huron, Am. Geol., VI, 1890, p. 22.

SMITH, W. H. C., Ann. Rep. Geo. Surv. Canada, 1890-1, map.

GREGORY, J. W., The Waldensian Gneisses and their Place in the Cottian

The reader will remember how often this principle was illustrated in our detailed account of contact-phenomena. It undoubtedly explained the greater perfection of the foliation in the long and narrow Winnipiseogee area than that in the broadly eliptical Ashuelot area or Main area. At the Bennington reservoir in the large size of the feldspar phenocrysts and their definite orientation with respect to the adjacent contact we have a good example of what characterizes the endomorphic zone of the Main area throughout the eastern contact as mapped. Within the zone the structure is much less determinate. Again, on Sandwich Mountain the porphyritic granite in and about the "permeation-area" described above, is largely granitic with the exception of those parts which display the fluxional habit about the horses. We are not without suggestion that the sudden changes of dip and strike within the cores of the igneous masses are largely the result of convection acting with massive pressure in the still viscid rock-body. Two miles from Weirs, on the highway to Meredith village, several outcrops appear in a clear field some three hundred yards to the right of the road. At one of these, a well-marked anticlinal arrangement can be observed in typical porphyritic granite. This structure is not part of a general system of parallel folds, nor of folds with any recognizable relation to the behavior of solid rock acted upon by lateral force. It is rather to be correlated with the irregular flow-structure assumed in the internal parts of many rhyolites; the well-known "felsites" of eastern Massachusetts furnish a good example.[1]

3. An analogous appearance will tend to characterize the margins between the intrusive rock and any foreign bodies which

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Sequence; Q. J. Geol. Soc., 1894, p. 249. On page 265 the author says of the foliation in these Alpine gneisses that it is "a contact-fluxion, and has no connection with the dynamo-metamorphism of the district. This marginal orientation also occurs on a microscopic scale. Mr. C. L. Whittle has described good examples in the contacts of the Connecticut Triassic lavas.

BONNEY, T. G., Some Notes on Gneiss; Geol. Mag., 1894, p. 118.

[1] Cf. MEHNER, "Fluctuationstructur" described in certain of "die schiefrigen Porphyren" of Westphalia; Tsch. Mitth., 1877, p. 177.

are caught up from the surrounding terranes.[1] In many cases, however, it is due not only to differential cooling, but to the pulling of the horses along in the direction of the migrating viscid magna. Such is the case with the examples of the circumferential arrangement of feldspars noted on Sandwich Mountain, on Saddle Hill, and in the Fitzwilliam area, and elsewhere.

4. Many observers have described the orientation of horses parallel to the margins of contact in cases where the inclusions have distinct elongated form.[2] The latter condition is usually furnished in the case of fragments derived from a country-rock with plane-parallel-structure. Consequently, we can understand this very general marginal arrangement described in all of the principal areas.[3]

5. The greater the heterogeneity among the constituents of the igneous body at the time of proximate consolidation, the more pronounced will be the flow-structure.[4] As suggested by Bonney,[1] horses may be melted up and thus give local variations in the mineralogical constitution of the igneous body. "Banding" is sometimes produced by the imperfect mixing of more

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[1] LAWSON, The Geology of the Rainy Lake Region; Ann. Rep. Geol. Surv. Canada, 1887-8, F, 137-138. BARLOW, op. cit., p. 29. DAKYNS and TEALL, On the Plutonic Rocks of Garabal Hill and Meall Breac; Q. J. Geol. Soc., 1892, p. 106. KOTO, B., The Archæan Formation of the Abukuma Plateau; Jour. Coll. Sci. Imp. Univ., Tokio, 1893, p. 288. GREGORY, Q. J. Geol. Soc. 1894, p. 242.

[2] DUROCHER, Mém. de la Soc. Géol. de France, 2e sér., t. VI. See his descriptions of several gneiss-granite contacts in Scandinavia; LEHMANN, Untersuchungen über die Entstehung der altkryst. Schiefergesteine. Bonn, 1884, pp. 16, 21; GEIKIE, A., op. cit., p. 39; GRANT, U. S., Field observations on certain granitic areas in northeastern Minnesota; 20th Ann. Rep. Minn. Surv., 1891, p. 40.

[3] Cf. EMERSON, Bull. Geol. Soc. Am., I, 1890, p. 559.

[4] Geol. Mag., 1894, p. 119. Cf. BONNEY, *ibid.*, 1894, p. 118. C. CHELIUS has recently described a stage leading to the complete fusion of enclosed masses, which is of interest. In this case granite cuts diorite and includes so many lenses of the latter in parallel arrangement as to simulate a "grobflaseriger gneiss." Notizbl. d. Ver. f. Erdk. Darmstadt, IV, Folge, 14 Heft, 3–8, 1893. Ref. in Neu Jahrb., 1895, p. 72.

J. J. SEDERHOLM speaks of "Schlieren" rich in mica and garnets in the "druckschieferiger Granit" of Finland. They are taken to represent remnants of schist-inclusions which have been dynamically metamorphosed. Om Börggrunden i Södra Finland, 1893. Ref. in Neu. Jahrb., 1895, p. 335.

than one phase of a magma.[1] It is conceivable that it might be locally brought about by the pulling out of basic segregations in a plutonic rock by mechanical force operating during or after complete consolidation.

On the road along the north shore of Wickwas pond a striking phase of the porphyritic granite was found which had been discovered before but never in such perfect development. It forms a strongly schistose mass a few inches thick which lies parallel to the foliation of the normal rock. Composed largely of brown biotite with here and there a large feldspar phenocryst, it is very different in appearance. With the biotite large apatites and considerable masses of titanite and magnetite make up the groundmass. This band had much the appearance of a shear-zone, like that described in the crystallines of the Malvern Hills.[2] But the microscope discloses no strong evidences of crushing in the feldspars which are clearly original or primary in their nature. Now there are plenty of cases on record where biotite segregations in granitic rocks grow to large size. Those at Graniteville, Missouri, vary from a few inches to five feet or more in diameter.[3] It may be that this and similar local bands in the rock in question are due to the tailing out of such segregations before the final solidification of the whole rock had set in. The resulting bands would thus be parallel to neighboring structure-planes and take their place as primary elements in a fluxional mass.

But the most favorable chance for the exhibition of a parallel structure over large areas would be given in cases where there is more than one generation of minerals; *i. e.*, in porphyritic rocks. Such, indeed, has been the character of most of the plutonic rocks where extensive flow-structure has been described. The large size of the phenocrysts of the porphyritic granite is one of the chief conditions leading to this peculiar and widespread foliation. Possessed of large growth before the final magmatic crystallization set in, each feldspar phenocryst was, as it were, of the nature of a foreign body embedded in the matrix. Thus, it would behave in the same manner as the truly exotic inclusion and a conspicuous alignment would result. It was observed in the field that, as a rule, the greater the dimensions of the phenocrysts, the more clearly was the structure displayed.

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[1] HARKER and MARR, Q. J. Geol. Soc., 1891, p. 283; A. GEIKIE and TEALL, *ibid.*, 1894, p. 656.

[2] Q. J. Geol. Soc., 1889, p. 477.

[3] Geol. Surv. Missouri, Ann. Rep., VIII, 1894, p. 154.

It is clear that the porphyritic granite with its elongate feldspar phenocrysts abundantly fulfills this criterion. In fact, the study of it suggests that plutonic rocks would more generally show a flow-structure were their constituents more varied in shape and relative size from the usual forms.

Quite rarely a broad banding is observable which is the result of the juxtaposition of layers containing different proportions of the phenocrysts.[1]

6. The negative criterion is valuable and in this New Hampshire case is most conclusive. If it can be shown that mountain-building could not induce the parallel structure in any secondary fashion, *i. e.*, by the pressure-metamorphism of consolidated, igneous or sedimentary rocks, we can fairly assume that the only other recognized cause has been operative. The evidence necessary therefore is threefold.

First, it may be derived from the study of foreign inclusions. The schistosity of the horses in all the observed localities where they occur within the porphyritic granite was evidently produced before the existence of that rock in its present state of crystallization. In practically all cases where comparison was possible, the excellence of this structure in any one inclusion was reflected in its parent-terrane. As the one varied from massive to schistose with a high degree of fissility, so did the other. Now the perfection of the schistosity was found to be irrespective of the attitude of the horses, *i. e.*, whether they were in parallel arrangement or not. Callaway used the correlative of this principle as an aid in determining the nature of the foliated granites of Northern Donegal.[2] He finds in them inclusions of massive diorites. His conclusion is, that on any theory of a mechanical origin for the foliation, it would be "hard to explain the escape of the diorite inclusions from the same influence." But if the intrusion of the porphyritic granite followed the period of plication and metamorphism, we should expect it to follow commonly the structural planes of the preëxisting schists.[1] Again referring to our detailed description of contacts in the three large areas, it will be seen how commonly this is the case. The intrusions are batholitic in their nature. They entered the overlying rocks by melting[2] their way through the axial zones of flexures. It is for this reason that the general distribution of these granite bodies is along the strike of terranes in this part of New Hampshire. The equivalence of strike and dip in the region in the narrow part of the "Fish-hook" north of Squam Lake between the foliated igneous rock and the adjacent schists is especially conspicuous.[3] Such pronounced apparent conformity is probably owing to an exchanging of the usual batholitic form of intrusion for a sill or sheet-form.

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[1] Cf. G. H. WILLIAMS, Bull. U. S. Geol. Surv., No. 28, p. 26.

[2] READE, Origin of Mountain Ranges, p. 139.

Secondly, the study of apophyses will be of much consequence. If we there see parallelism of the minerals composing the intruded tongue to its walls, no matter what the compass-direction of the apophysis may be, it is evident that the structure cannot be referred to mechanical deformation applied after the cooling of the whole intrusive mass.[4] Scheerer early described an occurrence of the opposite of this.[1] He determined that the red gneiss of the Erzgebirge is plainly eruptive into the gray gneiss. The apophyses of the former have a distinct parallel arrangement among the constituents. It is, however, not parallel to the walls, but inclined to them. He, hence, concludes that it is due to pressure exerted after the consolidation of the ancient granite.[2] That the apophyses should be as coarsely porphyritic as the main body, is of itself a strong suggestion of the exotic origin of the latter.[3] As we have seen, such is the case with the porphyritic granite, and in many instances, as on Saddle Hill, on Sandwich Mountain, in the Greenfield dike, and at Fitzwilliam, the apophyses have a more or less well-developed foliation, parallel to the walls and transverse to the structure-planes of the schists.

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[1] See GÜMBEL, op. cit., p. 522, 523, 524. He describes "Lagergranite" intruded into various schists. It is rather remarkable that his "Krystallgranit" of Bavaria does not possess a decided flow-structure. The rock is very similar to the porphyritic granite otherwise. Cf. also LAWSON, Ann. Rep. Geol. Surv. Canada, 1885, CC, p. 73, LEHMANN, op. cit., pp. 10, 23; WILLIAMS, G. H., Proc. A. A. A. S., 1887, XXXVI; Sect. E, p. 225; CALLAWAY, Geol. Mag., 1887, p. 354; LAWSON, Ann. Rep. Geol. Surv. Canada, 1887–8, F, p. 32; DANZIG, Mitth. aus dem Min. Inst. der Univ. Keil Bd. I. heft 1, 1888, p. 66; BARLOW, Am. Geol., VI, 1890, pp. 21–22; HARKER and MARR, op. cit., p. 284; ADAMS, Jour. of Geol., 1893, p. 334: SMITH W. H. C., Bull. Geol. Soc. Am., 1893, p. 338.

[2] From the author's previous statements there is no evidence that melting took place in connection with these intrusions. [ED.

[3] See the map of Hunter's Island by Mr. W. H. C. SMITH, which shows a very remarkable parallelism of the foliation in his "granite gneiss" with the strike of the enclosing schists. Ann. Rep. Geol. Surv. Canada, 1890–1.

[4] LAWSON, The Geology of the Lake of the Woods Region; Ann. Rep. Geol.

Lastly, while the porphyritic granite shows in certain areas evidence of strain, there is none of that very intense crushing which might be looked for if the foliation were of a mountain-built origin.[4] The signs of pressure in some of the phenocrysts may be due to the shearing set up among them in the tough, but still viscid magma, just on the instant of final consolidation. At the south end of the Ashuelot area we have the most schistose phase of the rock. It has evidently been squeezed to some extent. It is crumpled and even changed to an augen-gneiss whose lenticular feldspars represent the idiomorphic phenocrysts of the original rock.[5] Small faults of a half foot throw were observed in the Winnipiseogee area, just

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Surv. Canada, 1885, CC. p. 83, DANZIG, Ueber die eruptive Natur gewisser Gneisse sowie des Granulits im sächsischen Mittelgebirge; Mitth. aus dem min. Inst. der Univ. Kiel. Bd. I, Heft 1, 1888, p. 67. REUSCH, Neu. Jahrb., Beil. Bd, V., Heft 1. 1887, p. 57.

[1] Die Gneisse des sächsischen Erzgebirge; Zeit. d. d. geol. Ges., 1862, pp. 122–123.

[2] Credner attempted to prove that the red gneiss of the Erzgebirge is of sedimentary origin and not eruptive, as held by von Cotta, Scheerer, Stelzner, and others. Zeit. d. d. geol. Ges., 1877, p. 757.

[3] Cf. MCMAHON, Geol. Mag., 1888, p. 63; Q. J. Geol. Soc., 1893. p. 357.

[4] Cf. LAWSON, The Geology of the Rainy Lake Region, Ann. Rep. Geol. Surv. Canada, 1887–8, F, pp. 137–138.

[5] Cf. HAWES, Geol. of N. H., III, p. 214.

north of Wickwas pond. But there is nothing to indicate that any batholite as a whole has undergone any such enormous stresses as have affected the anorthosite of Canada, the protogine of the Alps, or even the gneisses of the Malvern hills.[1] Under the microscope the New Hampshire rock always shows that the essential minerals crystallized in place and that they have only been affected, except locality, by moderate pressures.

From the complete satisfaction of these several criteria one cannot escape the conviction that the foliation of the porphyritic granite has nothing to do with stratification, and has not been caused by the alignment of the constituents in a time of pressure metamorphism acting on a consolidated rock.

The significance of the uniformity of the porphyritic granite and its wide geological distribution.— One of the most striking characteristics of the porphyritic granite is the lithological sameness which pertains to it to a great degree throughout all the areas examined. This property is retained irrespectively of the nature of the rock-terranes which it invades. From the many examples of endomorphic changes induced in plutonic rocks by the melting up of foreign inclusions, we have selected a few which are described in the annexed footnote.[2] In view of this principle, it may be asked, why does the porphyritic granite not show more variations of mineral content? To this question we have no conclusive answer. It is possible that the rock which now fills the areas of the porphyritic granite was in general not at a temperature high enough to cause vigorous melting up of the walls, and that the great spaces in the earth-crust now filled by the granite were opened during the passage upward of earlier and hotter parts of the same magna. However this may be, the difficulty remains just as great for any theory of a metamorphic origin for the granite. It is impossible to believe that a rock with such continuity of like characters should have resulted from the alteration of the stratified or schistose rocks in the accompanying terranes of New Hampshire. Although the determinations of relative age among these terranes are as yet necessarily imperfect, we know that the porphyritic granite is in contact with rocks of many different horizons and of very variable composition. From this fact, it seems reasonable to conclude that the porphyritic granite is an exotic eruptive, finding its source of supply elsewhere than in any metamorphic center in immediate connection with the encircling schists. McMahon lays considerable stress on this idea in his argument for an eruptive origin of the Himalayan granites.[1] Lawson, in his study of the Laurentian gneisses, and Barlow, in a similar problem among the ancient rocks north of Lake Huron,[2] refer their "irruptive" masses to a fusion of the granitic floor on which the post-Laurentian rocks were laid. The New Hampshire rock is thus, in respect to its origin, more closely allied to the Himalayan granite than to the gneiss of the Canadian Laurentian.

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[1] CALLAWAY, Q. J. Geol. Soc., 1887, p. 525.

[2] Michael Lévy finds that by an endogenous action granulite cutting diabases and diorites is enriched in plagioclase at the contact (Bull. de la Soc. Géol. de France 1882–3, p. 296). Lehmann states that where the granitite of Döbeln is intruded into biotite-bearing rock, it is practically unchanged, but when it cuts in contact with sericitic schists, siricite is an important constituent (Untersuch. über Ent. d. altkryst. Schiefergesteine, Bonn, 1884, p. 19). Again, on classic ground, Lawson determines his Rainy Lake eruptive rock to be a quartzose biotite-granite gneiss where it comes in contact with quartz porphyries, yet the same rock-body cutting the more basic hornblende schists becomes a hornblende syenite with little quartz (Ann. Rep. Geol. Surv. Canada, 1887–8, F, 31). In one of the great batholites of western Massachusetts, Emerson notes three phasal differentiations, a heavy hornblende granite, a hornblende granitite, and a granite proper, all of which he attributes to the melting up of three various sorts of crystalline schists respectively (Bull. Geol. Soc. Am., I, 1890, p. 559). A similar affection of a porphyritic granite by a hornblendic country-rock is found in Chor Mountain, India (Geology of India, 2d ed., by Oldham; Strat. and Struc., p. 43); while quite recently Harker notes a good case of a relatively basic modification of granophyre at its junction with gabbro, and ascribes it mainly to an incorporation of re-fused gabbro (Q. J. Geol. Soc., 1895, p. 134).

Coarse veins cutting porphyritic granite.— McMahon and others describe plutonic eruptives intersected by dikes and veins of very similar material to that of which their hosts are composed. Besides the usual evidences of an eruptive origin for the Dalhousie gneissose granite of northern India, McMahon adds a criterion which is certainly without the weight of its associates, but which has been recently used more than once. He states that "the granite contains veins similar to those caused by shrinkage on cooling in granites of admittedly eruptive origin."[1] Emerson makes the principle more definite. Speaking of the largest granitic intrusion in Massachusetts west of the Connecticut River, he says: "The great mass is cut everywhere by a very great number of dikes of a coarse muscovite-granite, which seem to represent later intrusions of the central portions of the mass into shrinkage cracks in the already cooled peripheral portions, and thus to represent more truly its original composition."[2] This seems to be the best interpretation of those coarse dikes cutting the porphyritic granite composed of large individuals of the same minerals that make up that rock. They occur everywhere, though there is a concentration of them along the boundaries. With them are often associated the pegmatite veins of variable mineralogical constitution of aqueo-igneous origin and apparently without direct connection with the underlying magma.[3] On Gun Mountain, on Bear Hill, on the road following the valley of Rixford brook, and in the eastern area near New Hampton Centre, dikelike bodies of the former kind transect the porphyritic granite. Such localities suggest that in this respect also the main granitic mass is eruptive.

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[1] Geol. Mag., 1887, p. 216; Rec. Geol. Surv. India, XVIII, 1885, p. 106.

[2] Bull. Geol. Soc. Am., IV, 1893, p. 331.

The age of the porphyritic granite.—We have seen that the porphyritic granite intrusions were posterior to the stress-period during which the chief metamorphism of the New Hampshire rocks was brought about. The position of the axis of flexure determined largely the shape of the different important areas. Each one is batholitic in its nature. Since the eruptions ceased, no considerable deformation has occurred. In this, all the areas are alike, and from other facts, too, they were without much doubt essentially contemporaneous.

Now, the geologically highest fossiliferous zone within the mountain-built strata is the well-known one at Bernardston, Mass., some seven miles to the southwest of the Ashuelot area. The first studies of the organic forms enclosed in the limestones at this place referred them to the Helderberg or lower Devonian. More recent determinations now fix the age of the limestones as being at the Hamilton-Chemung stage of the Upper Devonian. They are folded up with quartzites and mica- and hornblende-schists which are intensely metamorphic. The careful field work of Professor Emerson and of the late Professor Dana has shown that these metamorphic rocks are a part of the same terrane which throughout this paper and the survey reports of the New Hampshire survey has been called the "Coös group." As early as 1873, Dana concluded that "the Bernardston, South Vernon, and Northfield beds being of Helderberg age, the Coös group, which is but the northern continuation of the same series, is, if correctly traced out, also Helderberg."[1] Professor C. H. Hitchcock adopted this view, although he disagreed with Dana as to the stratigraphic order of the rocks adjacent to the limestones.[2] Professor Emerson followed with the publication of his results after a painstaking lithological and structural study of the whole area. In this paper he most emphatically states his conviction and advances new proof that Dana's position was the correct one.[3] Two years later Dana reiterated his opinion,[4] and in his last and greatest work clearly shows that it persisted for the rest of his life.[5] Professor Emerson is inclined to place the faults and folds which dislocate the Bernardston rocks in Carboniferous or post-Carboniferous time. He attains this result by combining his observations at Bernardston with those in the more richly fossiliferous localities farther south, in the state of Massachusetts. Thus we may conclude that the porphyritic granite is probably a post-Carboniferous

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[1] Geol. Mag., 1887, p. 216.

[2] Bull. Geol. Soc. Am., 1890, p. 559. Cf. HARKER and MARR, Q. J. Geol. Soc., 1891, p. 284.

[3] Cf. BARLOW, Am. Geol., VI, 1890, p. 29.

[1] Am. Jour. Sci. (3), Vol. VI, 1873, p. 349.

[2] Am. Jour. Sci. (3), Vol. XIV, 1877, p. 380.

[3] Am. Jour. Sci. (3), Vol. XL, 1890, pp. 263 and 366; especially p. 366.

[4] *Ibid.* (3), Vol. XLIII, 1892, p. 456.

[5] Manual of Geology, pp. 310, 325.

intrusive and certainly younger than the upper Devonian at any rate.

Posterior to the schists, to the so-called protogines, and to other old eruptives on the one hand, the porphyritic granite is, of course, older than the aplitic and lamprophyric dikes which intersect it. It is also older than the Fitzwilliam granite, the hornblende granite stock of Mount Whiteface, the Franconia breccia,[1] and probably older than the complex stocks of the Waterville area. It is impossible with the facts now in hand to go further in fixing an epoch for these great intrusions. The porphyritic granite may even belong to the Tertiary.

SUMMARY.

Briefly stated, the chief conclusions which have been arrived at in the foregoing pages, are as follows:

1. The so-called "porphyritic gneiss" of New Hampshire is at least in the three most important areas, an eruptive porphyritic granite with a common tendency to develop planes of foliation.

It is not to be regarded as indigenous, that is, as the pure fused product of the surrounding formations — a deep-seated exotic origin must be posited for the granite. The evidences for an igneous instrusive origin include the composition and structure of the rock itself, the study of field-relations, the fluxional nature of the foliation, the uniformity of the rock in all its extent and the prevalence of secondary dikes and veins of injection apparently derived from the same magma. Besides these positive facts, there are also those embodied in what may be termed negative evidence. It includes all those observations that have been made in which the peculiarities of the region and of each intrusion will explain why some of the usual criteria of eruptive origins are not perfectly fulfilled. Chief among them is the fact of small certain and undoubted metamorphic effects at contacts — one which we have seen can be readily understood from the characters of the invaded rocks. Lastly, the contacts at first sight equivocal prove to be intrusive contacts on comparative evidence. The existence of zones of passage between the porphyritic granite and the schists with which it comes in contact is a fairly common phenomenon in the case of stocks of plainly eruptive material. Such transitions then form no inherent objection to a similar origin in this instance.

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[1] Geol. of N. H., Vol. II, p. 257.

2. The intrusions necessarily took place under great depth of strata. The latter were elevated by the last great period of White Mountain flexure and were practically holocrystalline products of the consequent metamorphism before the porphyritic granite was intruded. The subsequent disturbance of the greatest interest to us in this connection is that which caused the porphyritic granite to assume the parallel structure of flowage under differential stress analogous to that of the Himalayan and Alpine central granites. Since that time, the force operating on the terranes has been relatively slight. It has not sufficed to rub out completely, in any part, this initial structure of the porphyritic granite.

3. The molten rock entered the overlying schists in an irregular fashion but in general followed the regional line of strike of the White Mountain district.

4. Various considerations lead us to believe that the three areas of porphyritic granite described are virtually contemporaneous. They are, in every case, post-Devonian in age, — how much younger is unknown. Not being a basal formation, the terrane loses much of its value in an elaboration of the stratigraphic sequence and a reconstruction of the New Hampshire geological scale is necessary.

5. The porphyritic granite adds its testimony to the value of the opinion recently formulated among geologists that a highly important class of gneisses owes its parallel structure to fluxional movement. And it has the other general kind of interest in exemplifying the truth of Barrois' prophecy "que les terrains paléozoiques sont destinés à s'étendre de plus en plus sur les cartes géologiques aux depens des terrains primitifs."

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